

Integrated Design-Construction-Traffic Analysis for Highway Rehabilitation



(Construction Analysis for Pavement Rehabilitation Strategies)

USER GUIDE & MANUAL (V1.5a)

for

State (CA, FL, MN, TX, WA) Pavement Technology Consortium

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Prepared by

Eul-Bum (E.B.) Lee

Ph D, PE, PMP

Associate Researcher
Institute of Transportation Studies
University of California at Berkeley

510) 665-3637

eblee@berkeley.edu

<http://www.dot.ca.gov/hq/research/roadway/ca4prs/index.htm>

http://onramp.dot.ca.gov/newtech/offices/materials_and_infrastructure/rmi_branch/

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TABLE OF CONTENTS

Disclaimer	0
Table of Contents	1
Table of Tables.....	3
Table of Figures	4
1. Introduction	6
1.1. Highway Deterioration and Rehabilitation.....	6
1.2. Organization of the Manual.....	7
1.3. CA4PRS System Requirements	8
1.4. Additional Information Sources	8
2. CA4PRS Concept of Implementation	9
2.1. Development Background	9
2.2. CA4PRS Benefits and Payoffs.....	9
2.3. CA4PRS Implementation.....	10
2.4. CA4PRS Outreach.....	11
2.5. CA4PRS Enhancement Plan	11
3. Installation and Quick Start	13
3.1. CA4PRS Installation	13
3.1.1. Installation Procedure	13
3.1.2. Verification of the Deterministic Analysis	13
3.1.3. Verification of the Probabilistic Analysis	17
3.2. CA4PRS Quick Start.....	17
3.2.1. Project Details Input	20
3.2.2. Scheduling Input.....	20
3.2.3. Resource Profile Input.....	20
3.2.4. Analysis Input.....	21
3.2.5. Outputs and Reports	21
4. Analytical Modules.....	23
4.1. Concrete (PCC) Analysis Module	25
4.2. AC Overlay (CSOL) Analysis Module	25
4.3. AC Replacement (FDAC) Analysis Module	27
4.4. Interaction with <i>MultiCool</i>	27
4.5. Deterministic and Probabilistic Approaches	28
5. Logic and Algorithm	29
5.1. Analysis Procedure	29
5.2. Analytical Logic and Algorithm.....	29
5.3. Convergence and Sensitivity	31
6. Inputs and Outputs Interfaces	32
6.1. PCC Deterministic Inputs.....	32
6.1.1. Project Details Input Window	32

6.1.2. Scheduling Input Window	33
6.1.3. Resource Profile Input Window	35
6.1.4. Analysis Input Window	36
6.2. PCC Deterministic Outputs	39
6.2.1. Outputs and Reports	39
6.2.2. Multiple Analysis: Scenario Comparison	41
6.3. PCC Probabilistic Analysis Inputs	42
6.4. PCC Probabilistic Analysis Outputs	50
6.5. CSOL Analysis Inputs	50
6.5.1. CSOL Resource Profile Input Window	50
6.5.2. CSOL Analysis Inputs Window	54
6.6. FDAC Analysis Inputs and Outputs	56
6.7. Database Management	57
7. Traffic Impact Analysis module	63
7.1. Road User Cost Analysis	63
7.2. Traffic Data Measurement System: PeMS	69
8. Implementation Case Studies	73
8.1. Validation on I-10 Pomona	73
8.2. Application on I-710 Long Beach	73
8.3. Implementation on I-15 Devore	75
9. Technical Support	78
10. CA4PRS Terms and Abbreviations	79
10.1. CA4PRS Terms	79
10.2. CA4PRS Abbreviation	83
Appendix 1: CA4PRS Training Workshop	85
A.1.1: CA4PRS Training Workshop Overview	85
A.1.2: CA4PRS lab exercise	87
Appendix 2: PRE-EVALUATION QUESTIONNAIRE	90
A.2.1: Acronym Definition	90
A.2.2.: YOUR EVALUATION OF WORKSHOP	91
A.2.3: Acronym Questionnaire	92

[Appendix 3: I-15 Devore Project Brochure](#)

[Appendix 4: CA4PRS Journal Paper published in ASCE](#)

[Appendix 5: I-10 Pomona Reconstruction Proejct published in ASCE](#)

[Appendix 6: I-10 Pomona Reconstruction Proejct published in ASCE](#)

[Appendix 7: I-10 Pomona Reconstruction Proejct published in ASCE](#)

TABLE OF TABLES

Table 1: Categorized Major Parameters, Comparable in the <i>CA4PRS</i> Model.....	24
Table 2: Reference Data for Production Rates from Previous LLPRS Projects.	61
Table 3: Schedule, Delay, and Cost Comparison for I-15 Devore Closure Scenarios.....	77

TABLE OF FIGURES

Figure 1:Installation Step1 and 2 - Input Password and Installation Destination Folder.....	14
Figure 2:Installation Step3 and 4 - Input Backup Folder & Program Manager Group.....	14
Figure 3:Installation Step 5 and 6 - <i>CA4PRS</i> Database Installation in the Folder	15
Figure 4:Installation Step 7 and 8 - Installation in Progress and Completion.....	15
Figure 5:Start <i>CA4PRS</i> from Programs Menu in MS Windows	16
Figure 6: Opening Screen of <i>CA4PRS</i> Version 1.5a.....	16
Figure 7: <i>CA4PRS</i> Interface Hierarchy and Menu Tree	18
Figure 8: <i>CA4PRS</i> Help Menu and Contents	18
Figure 9: Opening the PCC Deterministic Analysis from the Database	19
Figure 10: <i>CA4PRS</i> Analysis Modules with Pavement Cross Section Changes.....	23
Figure 11: Lane Closure Schemes and Progress of Linear Scheduling	26
Figure 12: PCC Deterministic Input - Project Details Window	33
Figure 13: PCC Deterministic Input - Scheduling Windows	34
Figure 14: PCC Deterministic Input - Resource Profile Window	36
Figure 15: PCC Deterministic Input - Analysis Window.....	38
Figure 16: PCC Analysis Information - Construction Methods and Section Profile	38
Figure 17: PCC Deterministic Output - Production Details.....	40
Figure 18: PCC Deterministic Output -Production Chart with Linear Scheduling.....	40
Figure 19: PCC Analysis Output (Report and Save as a PDF file).....	41
Figure 20: Anlysis Unit Change (from Metric to English) in Input and Output.....	43
Figure 21: PCC Input and Output for Widened (14') Truck-lane Scenario	43
Figure 22: PCC Input for Scenarios Comparison-Weekend vs. Continuous Closures	44
Figure 23: PCC Output for Two Scenarios-Weekend vs. Continuous Closure	44
Figure 24: PCC Input for Two Scenarios - 203mm vs. 305mm Slab	45
Figure 25: PCC Output for Two Scenarios- 203mm vs. 305mm Slab.....	45
Figure 26: PCC Input for the Sequential Method	46
Figure 27: PCC Output for the Sequential Method.....	46
Figure 28: PCC Input for Two Scenarios - 12 vs. 24 hours Curing-time	47
Figure 29: PCC Output for Two Scenarios-24 vs. 12 hours Curing-time.....	47
Figure 30: PCC Input to Compare Multiple Alternative Scenarios	48
Figure 31: PCC Analysis Output Comparing Multiple Scenarios	48
Figure 32: Simulation Setting for Probabilistic Analysis.....	49
Figure 33: PCC Probabilistic Input - Scheduling Window	49
Figure 34: PCC Probabilistic Input – Resource Profile	51
Figure 35: PCC Probabilistic Input – Resource Examples	51
Figure 36: PCC Probabilistic Input – Analysis Window	52
Figure 37: PCC Probabilistic Output -Distribution and Sensitivity Charts	52

Figure 38: CSOL Deterministic Input - Project Details Window	53
Figure 39: CSOL Deterministic Input - Scheduling Window	53
Figure 40: CSOL Deterministic Input - Resource Profile Window	54
Figure 41: CSOL Deterministic Input – Analysis Windows.....	55
Figure 42: CSOL Analysis Input - Multi-Cool Window.....	56
Figure 43: FDAC Deterministic Input – Project Details Window	57
Figure 44: FDAC Deterministic Input – Scheduling Windows	58
Figure 45: FDAC Deterministic Input – Resource Profile Window	58
Figure 46: FDAC Deterministic Input – Analysis Window	59
Figure 47: FDAC Deterministic Input - Multicool Data.....	59
Figure 48: CSOL Deterministic Output - Production Details and Chart	60
Figure 49: FDAC Deterministic Output - Production Details and Chart	60
Figure 50: Database Management - Open Other Database File.....	61
Figure 51: References in the Help Main Menu	61
Figure 52: CA4PRS Reference Information on Caltrans DRI Website	62
Figure 53: Hourly Traffic Demand versus Roadway Capacity Graph.....	64
Figure 54: Delay in Vehicle-hour When Comparing Demand with Capacity	64
Figure 55: Open RUC Spreadsheet in the Tools Menu.....	65
Figure 56: Adjust Security Level to Low in MS Excel.....	65
Figure 57: Road User Cost – Main Input Window	66
Figure 58: Road User Cost – CWZ Capacity Determination.....	66
Figure 59: Road User Cost-Hourly Traffic Counts Input Window.....	67
Figure 60: Road User Cost- Hourly Lane Closure Input Window.....	67
Figure 61: Road User Cost – Main Output Window.....	68
Figure 62: Road User Cost – Demand Sensitivity Graph	68
Figure 63: Road User Cost – Capacity Sensitivity Graph.....	69
Figure 64: Caltrans/UC Berkeley PeMS Login at:.....	70
Figure 65: PeMS Real-time Traffic Condition on the Web	70
Figure 66: PeMS Configuration for the Loop Detector Station on I-880 High Street	71
Figure 67: PeMS Historical Database for Hourly/Daily Traffic Flow	71
Figure 68: I-880 Oakland (High Street) Daily Traffic Flow (PeMS)	72
Figure 69: I-80 Vallejo (Tennessee Street) Daily Traffic Flow (PeMS).....	72
Figure 70: I-10 Pomona Project with Half-Closure during One 55-Weekend.....	74
Figure 71: I-710 Long Beach Project during Eight Repeated 55-Hour Weekends.....	74
Figure 72: I-15 Devore Project with Two One-Roadbed Continuous Closures	77

1. INTRODUCTION

1.1. HIGHWAY DETERIORATION AND REHABILITATION

About 256,000 km of the National Highway System (NHS) connects 90 percent of the households and businesses in the nation. Many of the pavements on these highways were constructed during the infrastructure construction boom in the 1960's and 1970's with an infrastructure investment of more than \$1 trillion. They have far exceeded their design lives in less than 20 years due to continuously increasing traffic demand. Pavement deterioration on this highway adversely affects road user safety, ride quality, vehicle operation and highway maintenance costs, and traffic delays.

The majority of pavements on this highway network require major rehabilitation and reconstruction to preserve the integrity of the system. In recent years, state transportation agencies have shifted their focus from building new transportation facilities to “4-R” projects: restoration, resurfacing, rehabilitation and reconstruction. However, most major freeways in large urban areas operate under traffic-saturated conditions for long periods every day. Urban highway rehabilitation projects often create undesirable effects for state highway agencies, motorists, and commercial enterprises such as congestion, safety problems, and limited property access. To mitigate these problems highway planners, designers, and traffic managers should expedite construction in a variety of ways. Balance must be achieved between the need to minimize the costs of rehabilitation activities and the need to reduce the negative impacts that closures have on road users, the economy, and the environment.

In 1998, the California Department of Transportation (Caltrans) launched the Long-Life Pavement Rehabilitation Strategies (LLPRS) program a 10-year initiative to rebuild approximately 2,800 lane-km of deteriorated urban freeways among 80,000 lane-km of the state highway system. The purpose of the LLPRS program is to employ Caltrans' “Get-in, Get-out, and Stay-out” approach in providing “long-lasting, lower-maintenance pavement” for urban highways, an approach similar to that undertaken by state departments of transportation in Georgia, New York, and Wisconsin. LLPRS candidate projects have been selected from among California highways that experience a minimum average daily traffic (ADT) of 150,000 cars or 15,000 heavy trucks, and have deteriorated pavement structural condition and ride quality. Most of the candidates are concrete paved interstates in the urban highway networks of the Los Angeles and the San Francisco Bay areas. The increased need for highway rehabilitation has led to much research on construction methods and their impact on traffic flow. However, until now no

systematic research has been conducted, with the goal of integrating pavement materials and design, construction logistics, and traffic operations, which are essential to determining the most economical rehabilitation strategies. Linking that research to practical application in the planning of highway rehabilitation projects, *CA4PRS* (Construction Analysis for Pavement Rehabilitation Strategies) software has been developed as a sophisticated modeling and production tool for transportation agencies, highway construction planners, and contractors to use in evaluating construction alternatives.

1.2. ORGANIZATION OF THE MANUAL

This *CA4PRS* manual is divided into eight separate sections: Introduction, *CA4PRS* Concept of Implementation, Installation and Quick Start, Analysis Modules, Logic and Algorithm, Input and Output Interfaces, Implementation Case Studies, and Technical Support. There are two appendices as well. Appendix 1 includes a summary of the *CA4PRS* hands-on training workshop. Appendix 2 has the brochure for the Interstate-15 (I-15) Devore reconstruction project, an example of a *CA4PRS* implementation on a Caltrans LLPRS project.

The Introduction describes the need for the *CA4PRS* software along with the necessary system requirements. The *CA4PRS* Concept of Implementation section summarizes the development of *CA4PRS*, its capability, implementation experience, enhancement plan, and outreach efforts. The Installation and Quick Start section tells users how to install the software, check the sample project, and view results. In addition, the Installation and Quick Start section is designed to allow users to quickly verify the various capabilities of the *CA4PRS* program. The Analysis Modules and Logic and Algorithm sections describe various rehabilitation alternatives with typical example strategies and provides details about how the *CA4PRS* algorithm works. The Input and Output Interfaces section give the user detailed instructions on how to enter data, change default data, run *CA4PRS*, view the outputs, and export and import *CA4PRS* database files. The section on Implementation Case Studies summarizes three deployment projects, within urban highway networks in California, in which the *CA4PRS* program was calibrated, validated, and implemented. The Technical Support section has more contact information about the nominal *CA4PRS* technical support. Finally, the *CA4PRS* Terms and Abbreviations section summarizes commonly used definitions and acronyms in the *CA4PRS* analysis.

1.3. CA4PRS SYSTEM REQUIREMENTS

CA4PRS provides an easy-to-use and easy-to-learn tool that utilizes software interfaces that are familiar to the target end user. The CA4PRS software was developed to run on Microsoft Windows 95/NT4.098/2000/XP™ or higher operating systems and on computer systems with reasonably up-to-date hardware components. It is recommended that display settings of the computer monitor be set at a minimum resolution of 1024 x 768. All of the CA4PRS database and the code modules have been compiled to ensure that the user does not cause unforeseen errors. Please do not attempt to modify the database tables or code modules.

CA4PRS is developed in Microsoft Visual Basic 6.0 and utilizes a Microsoft Access 2000 database for data storage, although it does not require that Microsoft Access be installed to run the software. CA4PRS utilizes a number of royalty free third-party tools to enhance user friendliness, versatility of the user interface, and the presentation quality of the program. CA4PRS employs a multiple-document interface, similar to Microsoft Excel™ or Microsoft Word™, which enables multiple projects and analyses to be opened, viewed, and compared simultaneously.

1.4. ADDITIONAL INFORMATION SOURCES

For more detailed information with respect to technical aspects and its application of the CA4PRS analysis, please refer to the following documents:

- **Lee, E.B.**, and Ibbs, C.W., “A Computer Simulation Model: Construction Analysis for Highway Rehabilitation Strategies (CA4PRS).” *Journal of Construction Engineering and Management*, ASCE, Vol. 131, No. 4, pp. 449- 458, April 2005.
- **Lee, E.B.**, Roesler, J.R., Harvey, J.T., and Ibbs, C.W., “Case Study of Urban Concrete Pavement Reconstruction On Interstate 10.” *Journal of Construction Engineering and Management*, ASCE, Vol. 128, No. 1, pp. 49-56, 2002.
- **Lee, E.B.**, Lee, H.J., and Harvey, J.T., “Fast-Track Urban Freeway Rehabilitation with 55-hour Extended Weekend Closures: I-710 Long Beach Case Study.” *Journal of Construction Engineering and Management*, ASCE, Vo. 132, No. 5, pp. 465-472, May 2006.
- **Lee, E.B.**, Harvey, J.T., and Thomas, D., “Integrated Design/Construction/Operations Analysis for Fast-track Urban Freeway Reconstruction.” *Journal of Construction Engineering and Management*, ASCE, Vo. 131, No. 12, pp. 1283-1291, December 2005.

2. CA4PRS CONCEPT OF IMPLEMENTATION

CA4PRS estimates the maximum distance and duration of highway rehabilitation or reconstruction projects under a given set of project constraints, including pavement design, construction logistics, and traffic operations. When combined with traffic simulation models, the program helps agencies determine highway rehabilitation strategies that maximize the production schedule and minimize costs without creating unacceptable traffic delays. A knowledge-based computer model, *CA4PRS* utilizes the Monte Carlo simulation and critical path method (CPM) and linear scheduling techniques.

2.1. DEVELOPMENT BACKGROUND

The Institute of Transportation Studies (ITS), at the University of California at Berkeley (UCB), developed *CA4PRS* with an Federal Highway Administration (FHWA) pooled-fund grant (SPR 3(098)) sponsored by the State Pavement Technology Consortium (SPTC) (i.e., California, Minnesota, Texas, and Washington state departments of transportation). The American Concrete Pavement Association (ACPA) and the National Asphalt Pavement Association (NAPA) contributed partial funding for the field case studies in the validation process.

The input variables of *CA4PRS* are schedule interfaces, pavement design and materials, resource constraints, and lane closure schemes. These were identified by experienced transportation engineers and the research team to have the most significant impact on constructability. The model's logic and algorithm was reviewed and adjusted through technical committee meetings with the pavement industry groups (ACPA and NAPA). The *CA4PRS* program was calibrated and validated on projects throughout California and other sponsoring states with the collection of construction resources and schedule activity relationship data.

2.2. CA4PRS BENEFITS AND PAYOFFS

CA4PRS is designed to help highway agencies, consultants, and paving contractors make highway rehabilitation strategies that balance on-schedule construction production, traffic inconvenience, and agency cost. The *CA4PRS* model can also facilitate teambuilding among engineers from design, construction, and traffic operations to mutually arrive at optimal solutions in their decision-making processes. It is also a valuable tool for developing quantified information for communication with local communities affected by rehabilitation operations regarding such important topics as work periods, lane closure tactics, and use of local resources.

Added benefit comes when *CA4PRS* results are integrated with macroscopic and microscopic traffic simulation tools for estimating road user delay costs due to construction work zone closures, especially on high traffic volume urban networks. *CA4PRS* benefits transportation agencies during the planning and design stages of highway rehabilitation and reconstruction projects by: assisting in the development of staging construction-plans; establishing design level CPM construction schedules; estimating working days for cost (A) + schedule (B) contracts; checking contractor contingency plans; and calculating user costs for incentives/disincentives specifications. In addition, paving contractors and consultants will find this tool useful for checking construction staging plans, identifying critical resources constraining production, and quantifying the probability of meeting incentives/disincentives and cost plus schedule contracts.

2.3. *CA4PRS* IMPLEMENTATION

Since 1999, *CA4PRS* has been successfully implemented on high traffic volume urban freeway rehabilitation / reconstruction projects in California and other sponsoring states. The software was validated on the 2.8 lane-km Interstate-10 (I-10) Pomona LLPRS demonstration project (concrete), where it was used for the estimation of slab replacement using fast-setting hydraulic cement concrete as completed in one 55-hour weekend closure. The software was also used to develop the construction staging-plan for the Interstate-710 (I-710) Long Beach LLPRS demonstration project (asphalt), which was completed in eight 55-hour weekend closures two weekends ahead of schedule. The *CA4PRS* software was most recently used, in conjunction with traffic simulation models, to select the most economical rehabilitation scenario for the I-15 Devore project in San Bernardino.

The 4.5-km reconstruction project on I-15 in Devore, which *CA4PRS* estimates indicated would have taken 10 months using traditional nighttime closures, was completed within only two 9-day periods using one-roadbed continuous closures with around-the-clock construction. The innovative, integrated “Rapid Rehab with accelerated construction” approach on I-15 Devore saved \$2.6 million in agency costs while significantly reducing overall road user costs. Upcoming LLPRS projects, including I-15 Ontario and I-710 Compton, will implement *CA4PRS* to develop construction staging and traffic management plans to complete the work in the quickest way possible with the least impact to traffic.

CA4PRS helped Washington State Department of Transportation (WSDOT) engineers explore rapid rehabilitation strategies, compared to lengthy traditional reconstruction strategies, on two projects: Interstate-5 (I-5) in Federal Way, and beneath the Convention Center in Seattle. The latter section is one of the highest volume locations in Washington State and is currently under construction using a scheme of four weekend closures. In the 2004 construction season, the Minnesota Department of Transportation (MNDOT) implemented *CA4PRS* on two bituminous resurfacing projects on Twin Cities freeways in the Minneapolis area. Both jobs involved milling and bituminous paving: one was a nighttime operation on Interstate-494, and the other involved a combination of night and complete weekend closures on Interstate-393.

2.4. *CA4PRS* OUTREACH

CA4PRS has been presented several times in national conferences and workshops hosted by the Transportation Research Board (TRB), American Association of State Highway and Transportation Officials (AASHTO), and the FHWA. *CA4PRS* related research work has been published in a variety of transportation journals. It was introduced in articles in transportation magazines such TR News, and in the American Concrete Pavement Association (ACPA) and National Asphalt Pavement Association (NAPA) pavement industry newsletters. Hundreds of *CA4PRS* posters and brochures have been distributed to potential users, and information on the software is available on the Caltrans and UC Berkeley websites.

Caltrans' Division of Research and Innovation is currently conducting the *CA4PRS* outreach and deployment program by providing training workshops to pavement and traffic engineers in the contributing states, particularly in the metropolitan districts. Over the last three years, about 400 transportation engineers (design, construction, materials, and traffic) in the sponsoring DOTs have been trained by Dr. E.B. Lee (*CA4PRS* developer at UCB) in two-day hands-on training classes, and some are now capable of implementing the *CA4PRS* software in the rehabilitation analysis of actual projects. This *CA4PRS* workshop primarily focuses on the integration analysis of urban freeway rehabilitation under high traffic volume by taking into account long-life pavement performance, construction productivity, road user inconvenience, and limited agency budget. More details about the *CA4PRS* training workshop are included in Appendix 1.

2.5. *CA4PRS* ENHANCEMENT PLAN

CA4PRS is currently being upgraded with the FHWA pooled fund for the sponsoring DOTs to improve user friendliness and input interfaces, to add more rehabilitation strategies, and to integrate with the traffic analysis module. *CA4PRS* interim Version 1.1 will improve user friendliness and input interfaces for user convenience. For the upgrade of Version 1.5, some input parameters and construction alternatives will be

expanded to cover more variety of rehabilitation features such as the rehabilitation of continuously reinforced concrete pavement (CRCP) and dowel-bar retrofits. In the update for Version 2.0, the *CA4PRS* software will be integrated with a traffic delay analysis module based on the demand-capacity model (Highway Capacity Manual) to calculate road user delay in the construction work-zone. Eventually, the concept of the total cost (as the sum of agency and road user costs) based on the scheduling, traffic, and cost analyses will be provided in *CA4PRS* to select the most economical highway rehabilitation scenarios.

3. INSTALLATION AND QUICK START

The basic analysis of *CA4PRS* is designed to be straightforward. For the *CA4PRS* Quick Start, the I-15 Devore reconstruction project will be used as an example. To perform a *CA4PRS* analysis, the user will only need to verify that the example project can be analyzed using the *CA4PRS* Quick Start steps.

3.1. *CA4PRS* INSTALLATION

3.1.1. Installation Procedure

This section provides introductions for installing the *CA4PRS* software package as follows:

1. Run the *CA4PRS* setup file on the installation CD (i.e., *CA4PRS_v1.1_042505_setup.exe*).
2. Enter the password **SPTC** and choose the destination location (default is **C:\Program Files\CA4PRS**) where the *CA4PRS* is installed (Step 1 and 2 in Figure 1).
3. Choose the option (default is **Yes**) of backup copies of all files during the installation and select the Program Manager group (default is **CA4PRS**) to add the *CA4PRS* software icon to (Step 3 and 4 in Figure 2).
4. Choose the option (default is **Yes**) of installing a sample database which comes with the *CA4PRS* installation software and designate the location (default is **C:\Program Files\CA4PRS**) where the *CA4PRS* database should be installed (Step 5 and 6 in Figure 3).
5. Installation is will be in process and completed when **Finish** is clicked (Step 7 and 8 in Figure 4).

3.1.2. Verification of the Deterministic Analysis

This section briefly demonstrates how to check the *CA4PRS* software is running properly in the user's PC after the installation. More detailed instructions for the *CA4PRS* input and analysis processes are in the later sections. If the user encounters any system errors or the program crashes in the process of the validation, please contact the software developer.

1. Run the *CA4PRS* program in MS Windows with the main menu: **Start => Programs => CA4PRS => CA4PRS 1.1** (Figure 5).
2. Click **OK** on the opening screen (Figure 6).
3. To open the deterministic file, use the *CA4PRS* pull-down menu: **File => Open => PCCP Rehabilitation => Deterministic**.
4. Select "PCC Tutorial for I-15 Devore" project, the first in the list of the database samples, then click **OK**.
5. Go to **Analysis**, the last tab window, and check Metric is selected in the Unit toggle menu.

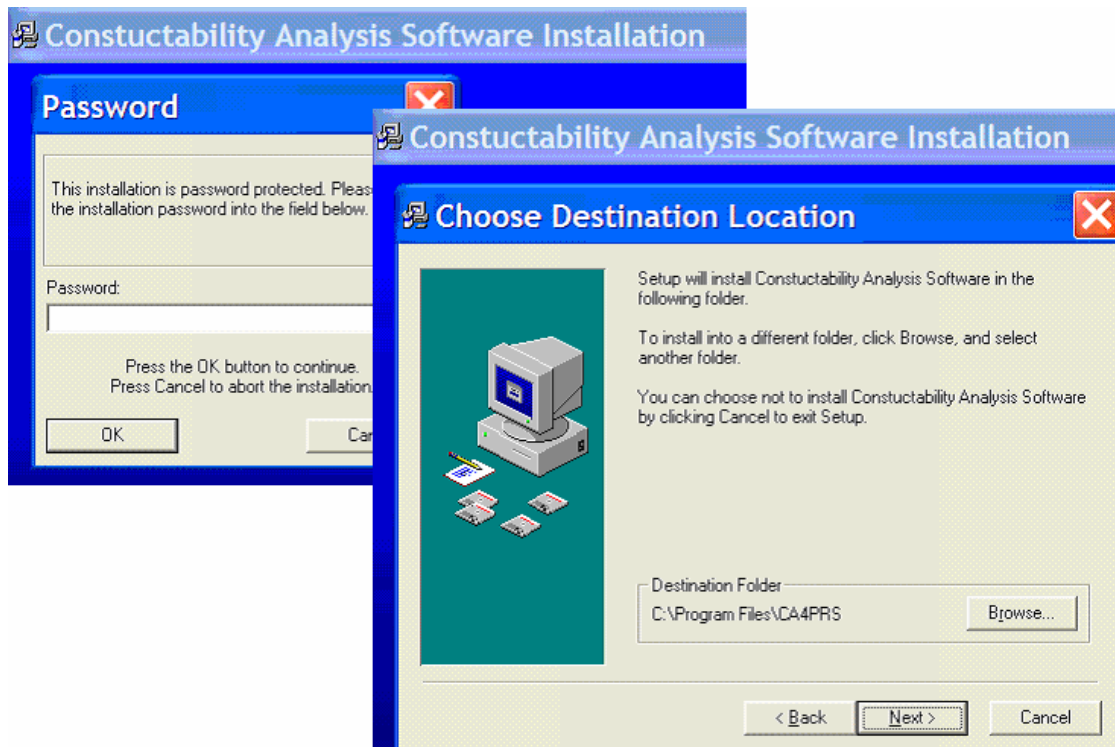


Figure 1:Installation Step1 and 2 - Input Password and Installation Destination Folder

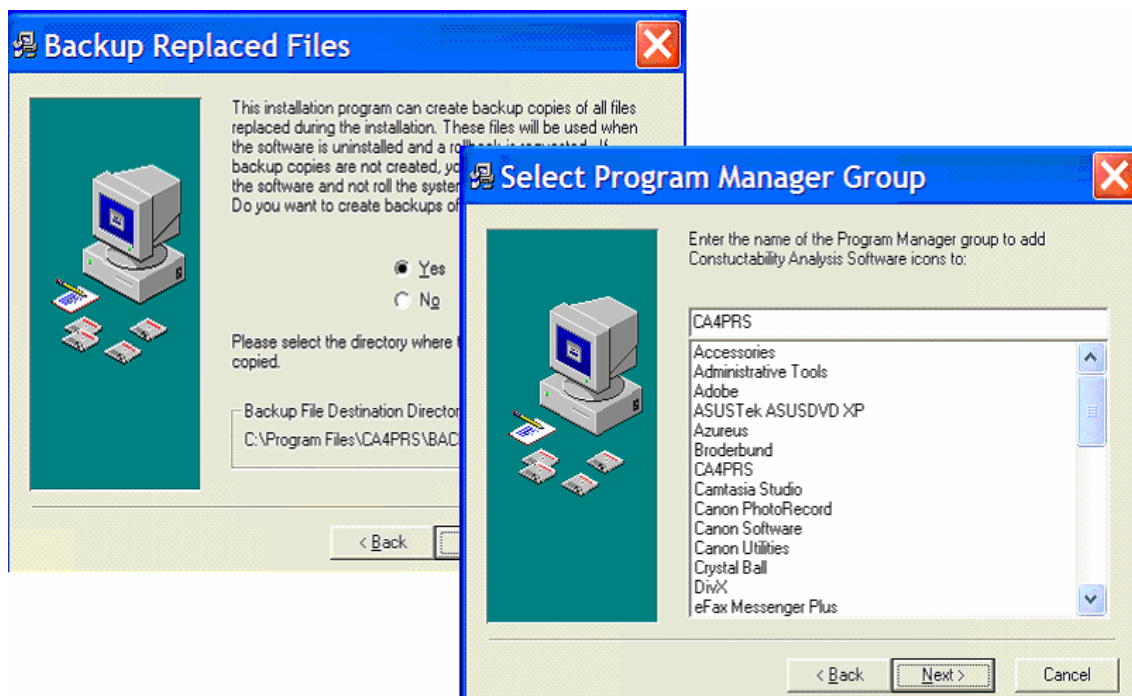


Figure 2:Installation Step3 and 4 - Input Backup Folder & Program Manager Group

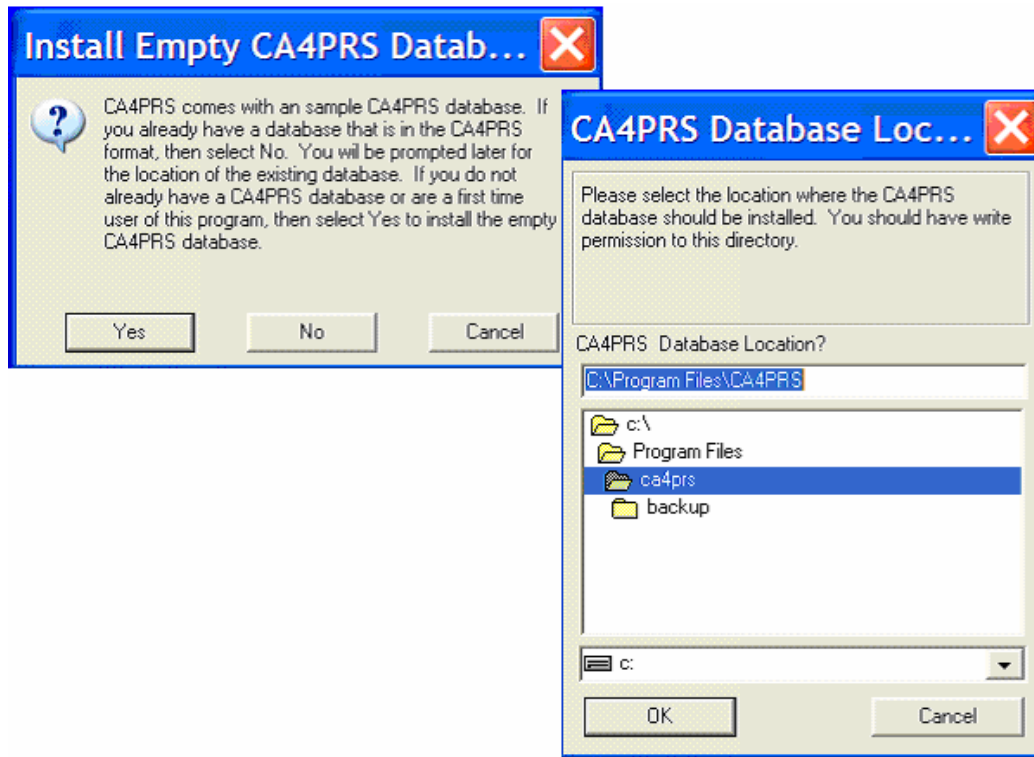


Figure 3: Installation Step 5 and 6 - CA4PRS Database Installation in the Folder

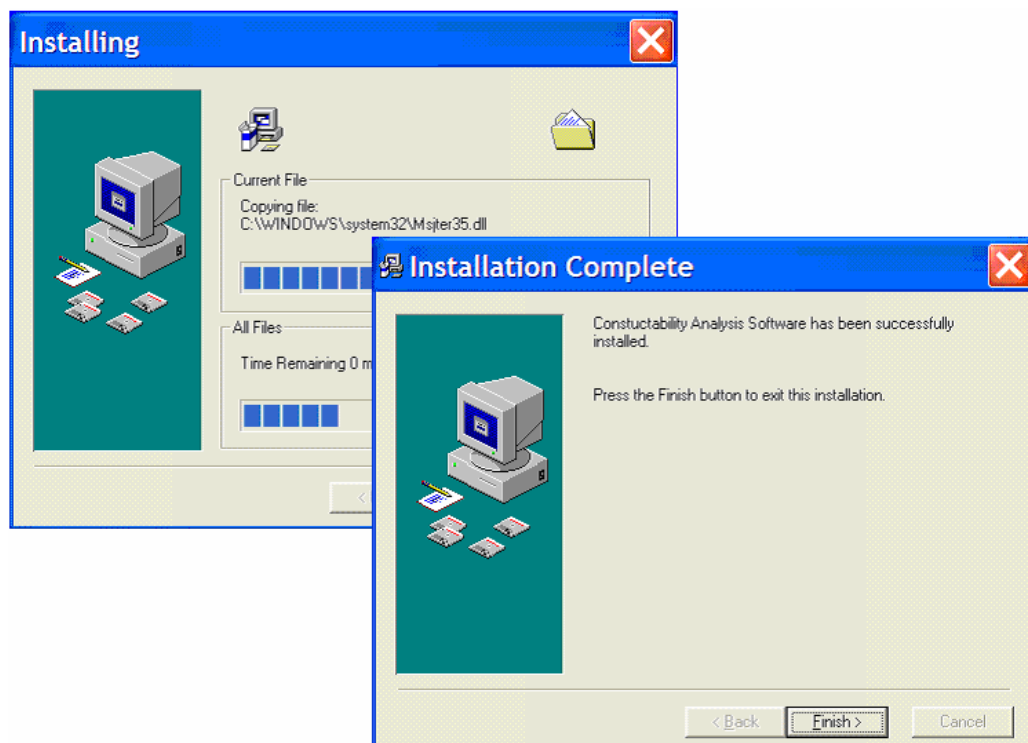


Figure 4: Installation Step 7 and 8 - Installation in Progress and Completion

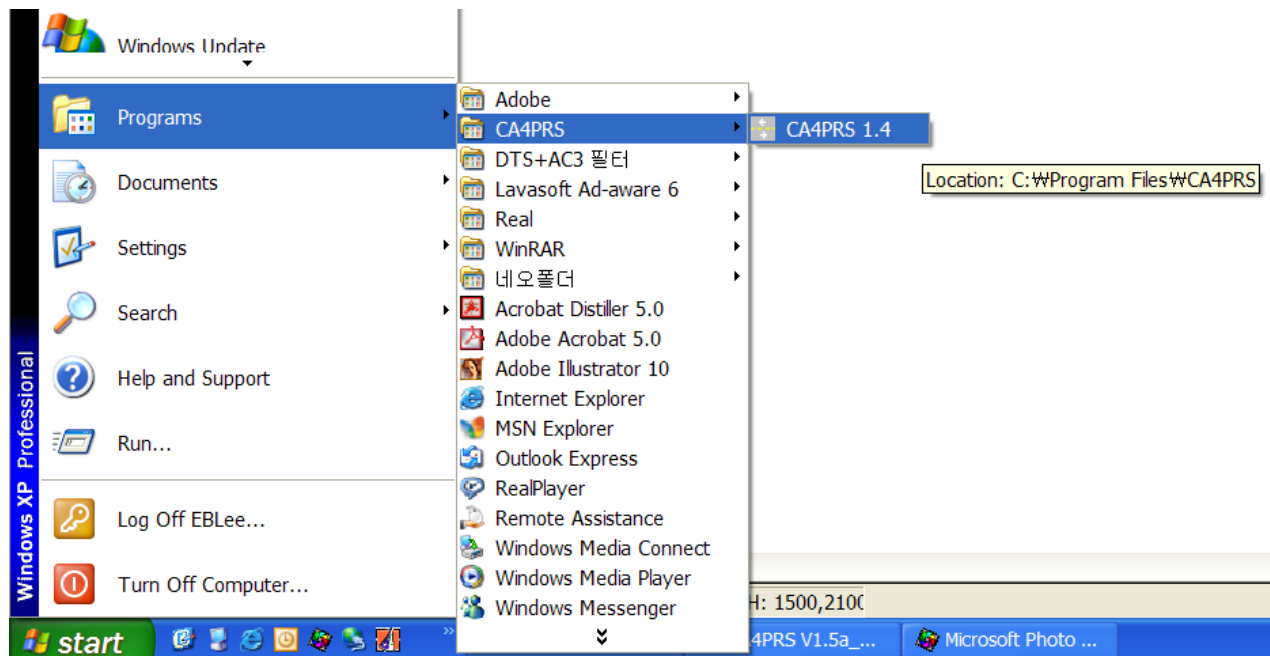


Figure 5: Start CA4PRS from Programs Menu in MS Windows



Figure 6: Opening Screen of CA4PRS Version 1.5a

6. Make sure the checked options (as defaults) in Analysis are: Continuous Closure/Continuous Operation in Construction Window, Concurrent Double Lane in Working Method, 12-Hours in Curing Time, and 305 mm in Section Profile.
7. Click **Analyze** at the lower-right corner.
8. Check that the “Maximum possible (c-l-km) = 1.41”, as highlighted in yellow in the output table.
9. Click **Close** in input and output to finish the validation of the deterministic analysis.

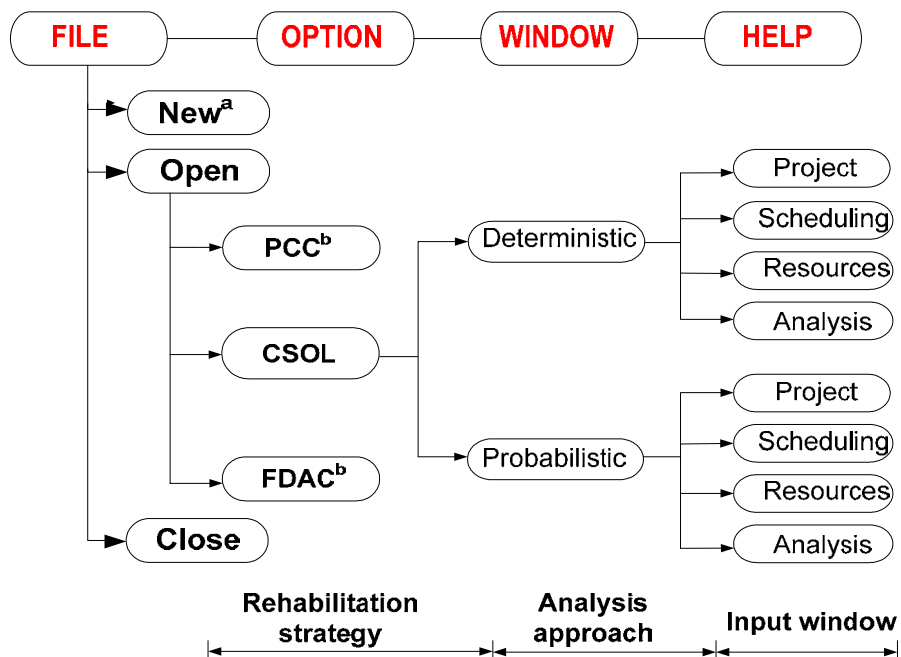
3.1.3. Verification of the Probabilistic Analysis

1. Open the probabilistic file from the *CA4PRS* pull-down menu: **File** => **Open** => **PCCP Rehabilitation** => **Probabilistic**.
2. Select Probabilistic “I-15 72-H Weekday (Probabilistic)” project, second in the list on the sample database, then click **OK**.
3. Go to the **Analysis** input tab window.
4. Click **Analyze**, then **Simulate**.
5. It will take 2 to 3 minutes to finish the probabilistic analysis. You will see the progress, and should not have any error message.
6. Check that the “Maximum possible (c-l-km) = 1.39”, as yellow highlighted on the output table.
7. Click **Close** in input and output to finish the validation of the probabilistic analysis.
8. Exit the program by selecting the main menu: **File** => **Exit**.

3.2. CA4PRS QUICK START

This section provides a brief description of inputs and outputs of the *CA4PRS* analysis. More detailed explanations of the analysis logic and algorithm are provided in section 4. Details of analytical modules and descriptions of the rehabilitation strategies are provided in section 0. More detailed definitions of major input variables with their reasonable ranges are provided in section 5 as is information on the interpretation of main outputs and reports.

CA4PRS employs a systematic menu structure that groups menu items in an intuitive manner. The *CA4PRS* pull-down menu is categorized into a hierarchy of rehabilitation strategy, analysis approach, and input window, as illustrated by the menu tree in Figure 7. More information about the definition and process of inputs and outputs is available through online help, which can be accessed from the main menu (Figure 8).



^aSub-structures for “New” are the same as those of “Open” below

^bSub-structures for “PCC” and “FDAC” are the same as those of “CSOL”

Figure 7:CA4PRS Interface Hierarchy and Menu Tree

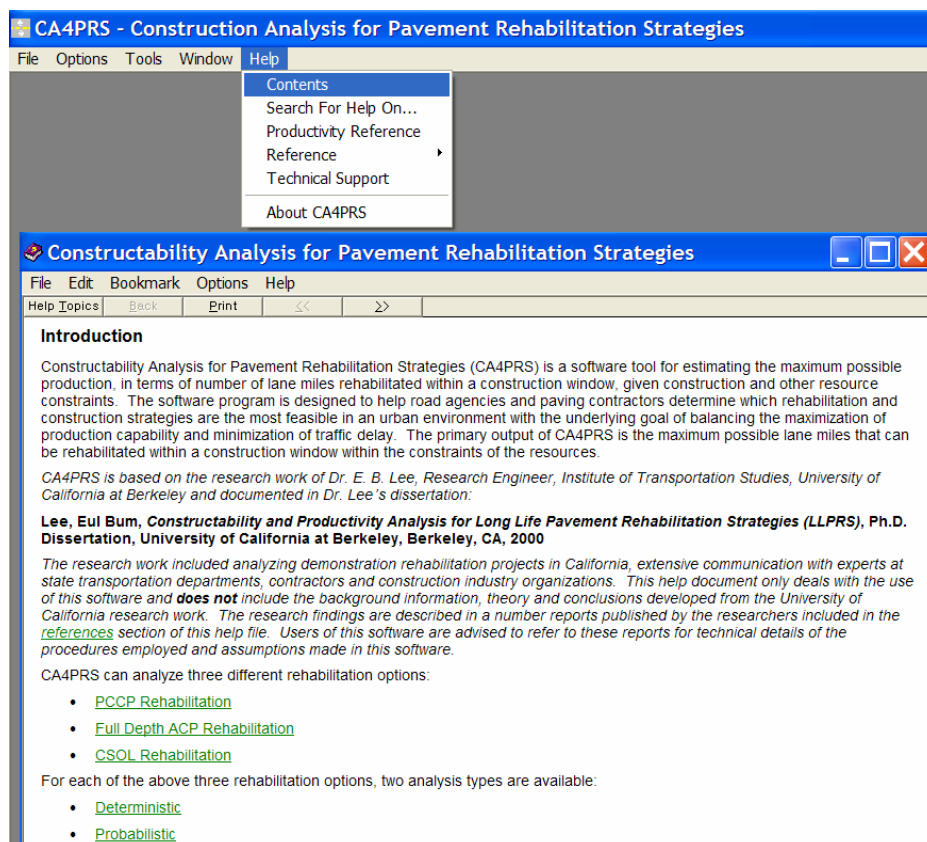


Figure 8:CA4PRS Help Menu and Contents

A quick start demonstration with the I-15 Devore reconstruction project from the sample database is provided, as an example of the PCC deterministic analysis. It can be opened from the *CA4PRS* main menu (**File => Open=> PCCP Rehabilitation => Deterministic**), as illustrated in the screenshot in

Figure 9. The user starts an analysis by either creating a new project, or opening an existing one, by inputting data into the four tab windows:

- **Project Details**
- **Scheduling**
- **Resource Profile**
- **Analysis**

The input configurations of the deterministic and stochastic modes are similar except that the former asks the user to specify absolute values for the uncertain variable (constant numbers). The stochastic model provides the user a list library of probability distribution functions to choose from.

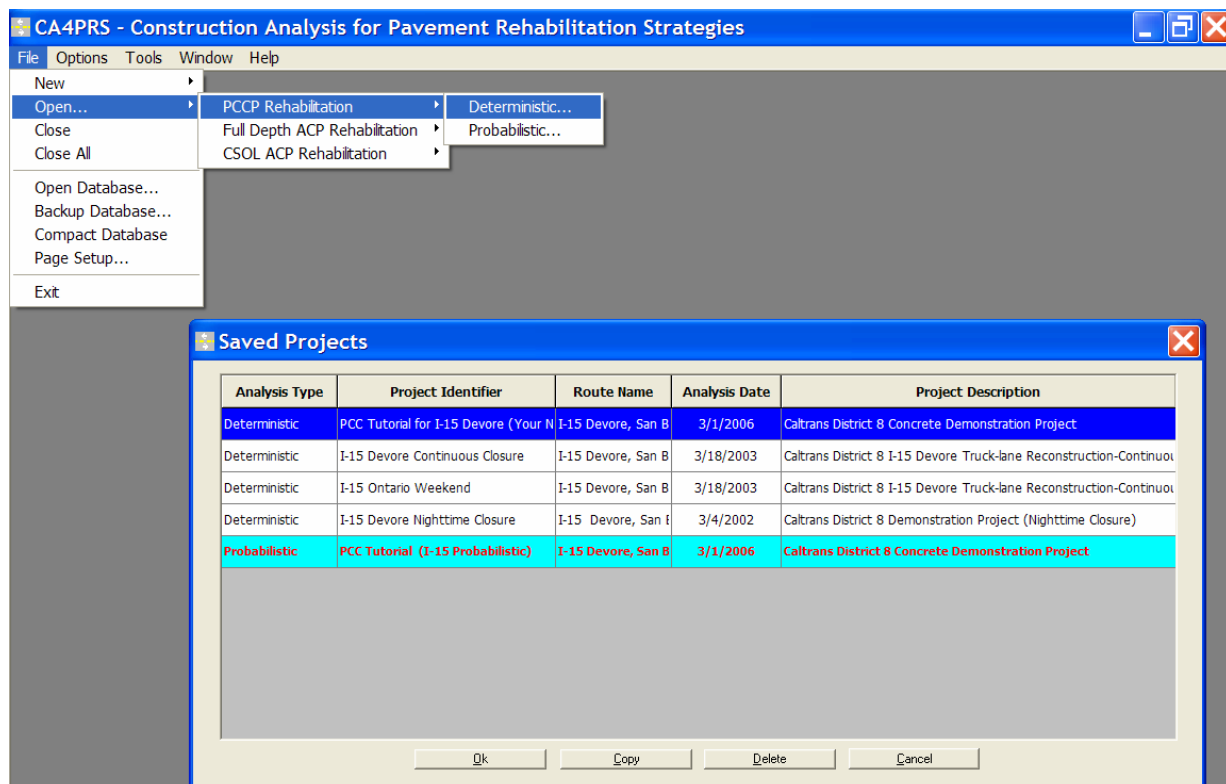


Figure 9: Opening the PCC Deterministic Analysis from the Database

3.2.1. Project Details Input

The **Project Details** window prompts the user to input basic information on the proposed project, including identifying project descriptions, route name, post (station) miles, location, etc. (refer to Figure 12 in section 5.1.1). In the project objective cell the user specifies the project scope by entering the total lane-km (or lane-mile) to be rehabilitated. This user-specified project objective (goal) then acts as the baseline to compute total number of closures required based on the rehabilitation production estimation of each scenario to be calculated at the end of the analysis.

3.2.2. Scheduling Input

The **Scheduling** input window categorized the scheduling aspects of the rehabilitation project into three sub-input groups: mobilization/demobilization variables, construction closures (windows), and activity lead-lag time relationships (refer to Figure 13 in section 5.1.2). A minimum time will be needed for such mobilization and demobilization purposes as site preparation, clean-up, and, more importantly, traffic control during construction.

Three alternative time frames (construction windows) are available: nighttime (typically weekdays), weekend, and continuous closures. The user has a choice of two continuous closure sub-options: 1) continuous closure with daytime-only shift operations, with one or two crew shift(s) for a limited number of weekdays while the freeway remains closed throughout the whole period of rehabilitation; and 2) continuous closure with continuous operations, which means fast-track accelerated construction with round-the-clock operations using two or three rotating crew shifts.

3.2.3. Resource Profile Input

The contractor's logistics and resource constraints are two of the most decisive factors in rehabilitation production, especially in fast-track urban highway rehabilitation where the space and access for construction equipment is often limited. The user inputs the number and capacity of the available equipment and plants in the **Resource Profile** input window. Some resource inputs will require the prior knowledge, experience, and personal judgment of the user (refer to Figure 14 in section 5.1.3). For instance, the user should input a reasonable number of demolition

hauling trucks per hour by taking into account the expected loading cycle time of the demolition and turn-around time of the trucks between the site and dumping areas.

3.2.4. Analysis Input

In the **Analysis** input window, as a main switchboard, the user selects and controls the following input categories (refer to Figure 15 in section 5.1.4):

- Construction windows
- Rehabilitation sequence with respect to lane closure tactics
- Concrete curing time or asphalt cooling time
- Pavement cross section changes
- Truck lane width

For each input category, a drop-down list of values or check box options is available. To analyze and compare various (multiple) options, the user can choose one or more variables. The asphalt analysis modules also allow the user to enter estimated cooling times for each AC lift, or choose the option to run the *MultiCool* software instead.

3.2.5. Outputs and Reports

CA4PRS analysis produces either a single or multitude of analysis results, depending on the number of input options the user selects. For example, if in the PCC analysis module the user elects to consider two concrete curing time options (4-hour versus 12-hour mixes), two rehabilitation sequence options (sequential single-lane versus concurrent double-lane methods), and two cross section profiles (203 mm slab replacement only versus 300 mm slab and 150 mm base reconstruction) for the 55-hour weekend closure, a total of eight analysis results, each displayed in separate output windows. Results are generated when the user clicks the **Analyze** button.

The output is presented in two parts: **Production Details** and **Production Chart**. Included in the production details screen are the user input summary and the main analysis results (refer to Figure 17 in section 5.2.1). The main results are the maximum production of each rehabilitation

scenario analyzed in terms of lane-km, and the total number of closures to complete the entire scope (objective) of rehabilitation project based on the maximum production under each scenario. Some additional information is also provided in the outputs, including a summary of material volumes for the major operations such as demolition, slab paving, and base paving. The main results of the CPM scheduling analysis are provided as well; i.e., the optimally balanced maximum duration of the demolition and paving activities within a given closure time limit. The production chart screen contains a “line of balance schedule” where the linear progress of the main rehabilitation operations is plotted against the time (refer to Figure 18 in section 5.2.1).

One of the most useful features of the *CA4PRS* outputs, especially from the contractor’s point of view, is identifying which input equipment constrains the operations. A list of input resources, with a comparison of the input number and the minimum number needed, is tabulated in the **Production Details** output window. The *CA4PRS* hierarchy provides extensive graphical and tabular outputs and incorporates a report feature that documents the analysis input and output for printing or saving as an Adobe Portable Document Format or Rich Text Format file (refer to Figure 19 in section 5.2.1).

4. ANALYTICAL MODULES

Three widely-accepted highway rehabilitation strategies incorporated in *CA4PRS* as individual analysis modules are: (1) the Portland cement concrete (**PCC**) reconstruction strategy in which the old pavement is rebuilt with a PCC slab and optional pavement base structure, (2) the crack-seat and AC overlay (**CSOL**) rehabilitation strategy in which the old pavement is optionally cracked/seated and overlaid with new asphalt concrete (AC) layers, and (3) the full-depth AC (**FDAC**) replacement strategy in which the old pavement is replaced with full-depth AC layers. The typical pavement cross section changes for these three rehabilitation strategies are shown in Figure 10. The categorized input variable for *CA4PRS* is summarized in Table 1.

To simplify the analysis it was assumed that a typical urban freeway segment has four traffic lanes in each direction. Since most passenger lanes within the candidate pavement sections are generally in good condition, it was further assumed that only the two outer truck lanes will be rebuilt while implementing the PCC reconstruction and FDAC replacement strategies, per Caltrans LLPRS practice. However, in the CSOL rehabilitation, the entire freeway, including shoulders, was assumed to be rehabilitated because it would otherwise create a sudden longitudinal drop-down along the pavement surface.

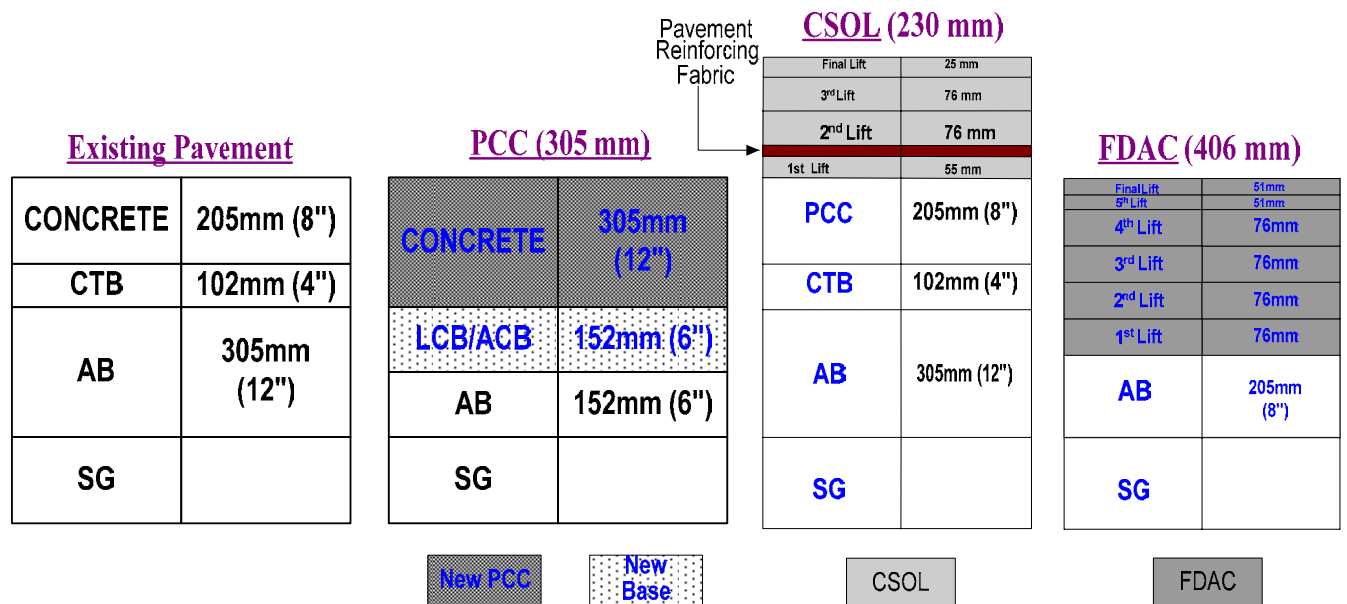


Figure 10: *CA4PRS* Analysis Modules with Pavement Cross Section Changes

Table 1: Categorized Major Parameters, Comparable in the CA4PRS Model.

Category	Options	
Rehabilitation Strategies	Concrete Rehabilitation or Reconstruction (PCC)	
	Asphalt Concrete	CSOL (Crack Seal and Overlay)
		Full Depth AC (FDAC) Replacement
Pavement Cross section	PCC	203-mm Slab
		305-mm Slab
		User defined cross section
	CSOL and FDAC	Multiple lift of layers
Scheduling Constraints	Construction Windows	Nighttime closure
		Weekend closure
		Continuous closure
	Schedule Relationship	Mobilization / Demobilization
		Activity lead-lag relationship
	Curing Time (PCC)	4 hours (Fast-Setting Cement)
		12 hours (Type III PCC)
		User specified curing time
Lane Closures and Rehabilitation Sequences	PCC	Function lift thickness and weather
	PCC and FDAC	Concurrent work method
		Sequential work method
	CSOL	Single-lane rehabilitation
		Double-lane rehabilitation
Contractor's Logistics and Resource Constraints	Demolition hauling trucks	Partial closure
		Full closure
	Paving material delivery trucks	Capacity and number per hour
	Batch plant	Capacity and number
	Paving machines	Speed and number

4.1. CONCRETE (PCC) ANALYSIS MODULE

Three alternative new pavement cross sections, i.e., 203, 254, and 305 millimeters are available in the built-in menu for the PCC reconstruction strategy. The user can create a cross section profile, if the default cross sections are not applicable to the project, including any additional demolition depth that might be necessary to comply with the new FHWA height clearance requirements for bridge underpasses or overpasses.

There are three default cement materials to choose from: 4-, 8-, and 12-hour curing time mixes to achieve a minimum traffic opening strength, e.g., 2.8 MPa (400 psi) of flexural strength with the 3-point beam test. Use of different concrete curing times allows for extra construction time that could not be attained using ordinary PCC. In addition to the available curing time in the menu, a user-defined concrete curing time is also available.

The PCC reconstruction module includes two lane closure alternatives: 1) full-closure, which makes possible the concurrent-method of simultaneous demolition and paving; and 2) half-closure, which dictates the sequential-method of demolition, followed by base paving, and finally slab paving (see Figure 11). The alternatives are further delineated by the choice of double-lane rehabilitation, in which both truck lanes are reconstructed simultaneously, or single-lane rehabilitation, in which one truck lane is separately rebuilt per closure.

In a full-closure scenario using the *concurrent-method* to achieve double-lane rehabilitation, the two outside truck lanes are reconstructed while the two inside lanes are used for construction access. The four lanes of the traffic roadbed on the other side of the construction roadbed are converted for two-way “counter flow traffic”, separated by a moveable concrete barrier (MCB) system. In the half-closure scenario using the sequential-method for a single-lane rehabilitation, a single truck lane is closed for reconstruction, while another lane is closed for construction access. Traffic is routed onto the remaining open lanes, with the MCB installed between construction activity and traffic. The more modest closure scenario leaves room only for the sequential approach.

4.2. AC OVERLAY (CSOL) ANALYSIS MODULE

The CSOL rehabilitation strategy usually involves placing three to four new AC layers, 200 mm to 250 mm in typical LLPRS designs, in most case on top of the cracked and seated old PCC pavement. The user is able to create a project-specific pavement cross section by specifying the

number of AC layers required and the layer thickness. *MultiCool*, a numerical AC cooling simulation program calculating cooling time for multi-layer paving, is embedded in *CA4PRS* to check the suspension of the paving operation due to the cooling time.

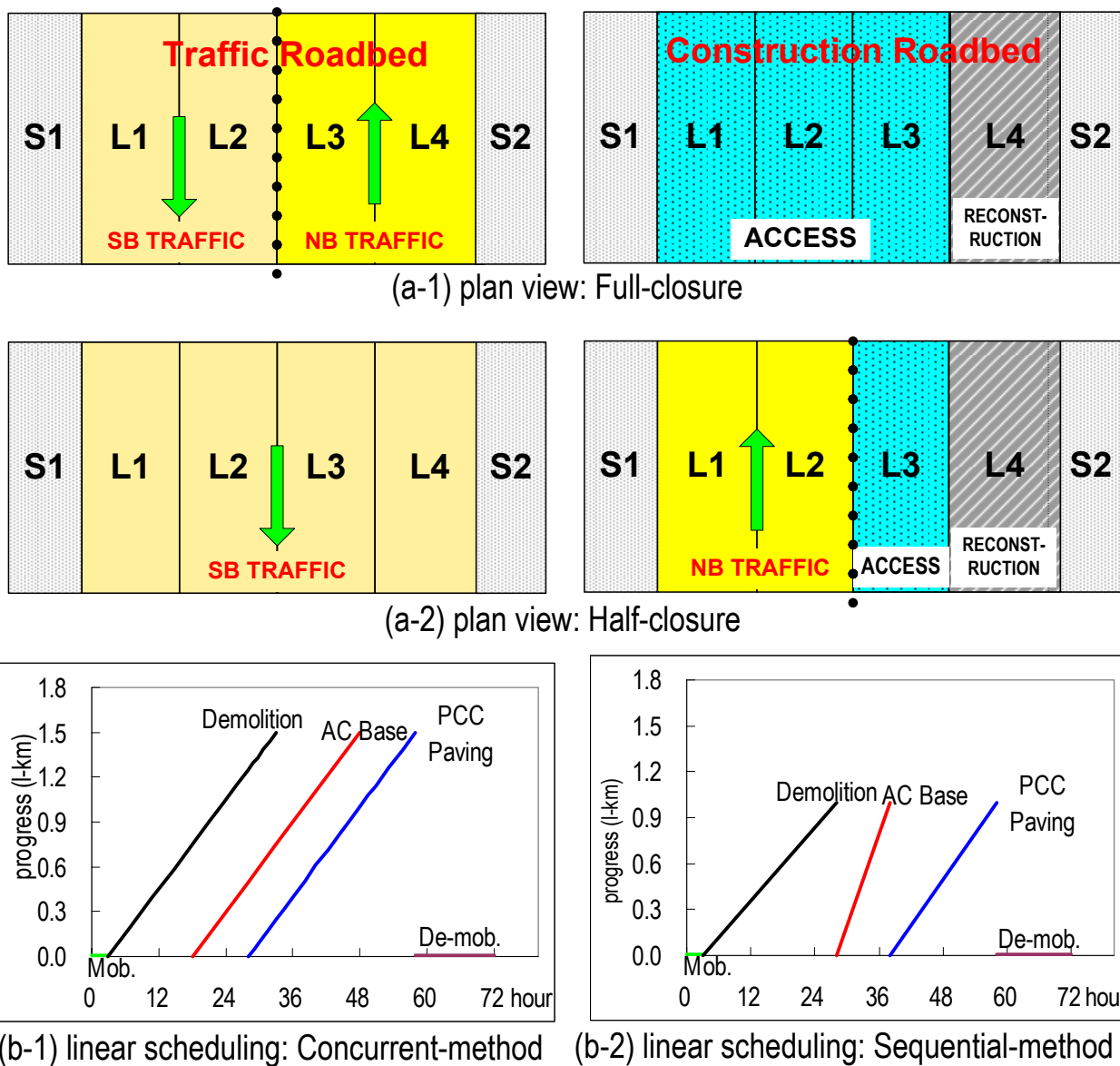


Figure 11: Lane Closure Schemes and Progress of Linear Scheduling

Two lane closure tactics are permitted in the CSOL analysis module: full- and half-closure. With CSOL full-closure, one direction of the freeway is completely closed for rehabilitation and traffic is switched to the other side of the freeway using median crossovers and counter-flow traffic. The

main lanes and shoulders are overlaid completely on one side of the freeway within a closure layer-by-layer and lane-by-lane. Usually, the paving operation alternates the sequence of paving lanes to minimize waiting time for AC cooling.

CSOL half-closure requires closing only two out of four lanes in one direction. The CSOL half-closure option has two sub-options: 1) CSOL half-closure with full-completion, in which all of the AC layers are placed on two lanes and traffic is shifted to the newly paved lanes while the other two are paved; and 2) CSOL half-closure with partial-completion, in which the first bottom AC layers are overlaid at the first closure and the remaining layers are completed at the subsequent closure.

4.3. AC REPLACEMENT (FDAC) ANALYSIS MODULE

The full-depth AC (FDAC) replacement strategy requires complete removal of the old pavement and partial trimming of the aggregate base (AB) to accommodate the specified depth of the new AC pavement. In LLPRS projects, a rich bottom AC layer will likely be placed on top of the re-compacted AB, followed by four or five AC layers paved sequentially, with a total thickness ranging from 305 to 381 mm. Similar to the CSOL module, the FDAC module allows the user to input project-specific AC cross sections, and *MultiCool* checks the suspension of the paving operation due to the cooling time.

The FDAC analysis module includes two lane closure tactics: single- and double-lane rehabilitation. A major benefit of double-lane rehabilitation is the interlocking of multiple AC layers by overlapping longitudinal joints between adjacent lanes.

4.4. INTERACTION WITH *MULTICOOL*

As discussed in earlier sections, *CA4PRS* provides the option of using user-specified or *Multicool*-calculated AC cooling times. These cooling times are the time required prior to the placement of the next lift or opening to traffic. In the user-specified option, the user specifies the cooling time for each of the lifts as part of the cross section definition for each design profile. *CA4PRS* optimizes the sequence of lift placement to minimize suspension time needed for cooling. In order to provide a seamless integration of *Multicool* with *CA4PRS*, *Multicool* analysis procedures were converted to a dynamic link library (DLL) and *Multicool* specific data are included as part of *CA4PRS* input when the *Multicool* option is selected. The environmental conditions are input for

up to four different periods per day, and *CA4PRS* interpolates numerical variables for the time of day of AC lift placement. *CA4PRS* calls *Multicool* to calculate cooling time for each lift of AC for each lane during each simulation. This is transparent to the user.

4.5. DETERMINISTIC AND PROBABILISTIC APPROACHES

CA4PRS provides dual analytical approaches in dealing with the input variables: deterministic or probabilistic. The program provides seamless transition between the deterministic and probabilistic analysis approaches allowing the user to easily transfer project data. In the deterministic analysis approach, the input parameters including resource and scheduling constraints (activity lead-lag time relationships) are treated as constants without any variations. The deterministic analysis seeks the maximum pavement section (length) that can be rehabilitated within the construction closure windows under the given project constraints. The deterministic analysis is faster and has fewer input data requirements than the probabilistic analysis.

In the probabilistic (stochastic analysis) approach, the input parameters are treated as random variables and are specified using the appropriate parameters for distribution of each variable selected. Uniform, Normal, Log Normal, Beta, Geometric, Triangular, Truncated Normal, and Truncated Log Normal probabilistic distributions are available, and any number of the scheduling and resource input parameters could be modeled as a probabilistic variable selected from a drop-down list. The probabilistic approach analyzes the likelihood of completing the rehabilitation production length (distance), utilizing Monte Carlo simulation. During the Monte Carlo simulation, *CA4PRS* generates random variables from the specified probabilistic distribution and repeatedly solves for the maximum rehabilitation length with each combination of the inputs.

One main difference between the probabilistic and deterministic modes is that the probabilistic outputs show a plot of the distribution of maximum production as a result of the Monte Carlo simulation. The probabilistic output, as a normalized distribution according to the Central Limit Theorem, represents the most likely maximum production as a mean, and productions at -0.5 standard deviation and +0.5 standard deviation as lower and upper bounds, respectively. Despite requiring more input information and more time to run, the stochastic formulation provides a more realistic estimation and comprehensive description of the rehabilitation production.

LOGIC AND ALGORITHM

This section describes the analytical process, logic background, and calculation algorithm of the *CA4PRS* model.

4.6. ANALYSIS PROCEDURE

The typical *CA4PRS* input procedure is as follows:

1. Choose the deterministic or probabilistic analysis mode.
2. Input the scope (lane-km) of the rehabilitation project.
3. Select a rehabilitation strategy (PCC, CSOL, or FDAC).
4. Define the new pavement cross section: slab and base thickness (PCC) or layer profile (AC).
5. Set the concrete curing time or AC cooling time (or let the *MultiCool* software calculate cooling times interactively).
6. Choose a construction window (closure timing and length): nighttime, 55-hour weekend, 72-hour weekday, or one-roadbed continuous closure.
7. Define the activity lead-lag relationships and minimum time interfaces between major operations.
8. Select construction sequences and lane closure tactics: full-closure (concurrent-method) versus half-closure (sequential-method) and single-lane versus double-lane rehabilitations.
9. Input the contractor's logistical resources (crew, equipment, and plants) for the major operations.
10. For all three rehabilitation strategies, *CA4PRS* analysis produces the following main outputs:
 - Maximum rehabilitation production (lane-km or centerline-km) per closure
 - Total number of closures and duration required to complete the entire project
 - Constraining resource(s) and optimum (minimum) amount of other resources needed to match the constraining resource(s)
 - Balanced time allocation between demolition and paving operations

4.7. ANALYTICAL LOGIC AND ALGORITHM

The major steps in the solution process for PCC reconstruction analysis are detailed below.

Using the resource profile, construction method, and pavement cross section, *CA4PRS* determines the rate of each of the main rehabilitation activities (unit length / time). *CA4PRS* determines the effective duration available for major rehabilitation operations after the mobilization and demobilization durations are accounted for within the construction window. Certain activities, such as concrete curing or asphalt cooling, can continue during demobilization, which is taken into account in determining the effective duration.

Based on the selected construction method (concurrent or sequential), *CA4PRS* identifies the groups of concurrent activities and, using the rate determined in step 1, the critical production activity within each group.

Using the linear scheduling technique for critical activities identified in step 3, *CA4PRS* determines the maximum rehabilitation length that can be achieved within the construction window.

The CSOL rehabilitation and FDAC replacement analysis calculate cooling time using *MultiCool*, an iterative approach finding the optimum production, which is described in the previous section. Since the cooling time of each lift of AC layer is a function of the environmental conditions during its placement and cooling, a direct solution is not possible. *CA4PRS* maximizes the rehabilitation length that could be achieved within the construction window iteratively and takes into account the optimum sequence of paving multiple layers and lanes. The first three analysis steps for CSOL and FDAC are identical to the PCC solution process described earlier. CSOL and FDAC steps 4 through 6 are as follows:

4. An initial rehabilitation length is estimated. Where demolition is involved, the initial rehabilitation length is based on demolition taking half the available construction window and, where there is no demolition, the initial estimate assumes that AC delivery trucks are the constraining resource.
5. Use linear scheduling and the rehabilitation length from step 4 to calculate each activity start and end time and any suspension time required for AC cooling or other constraints before the next activity can begin. The end result is the total time required for rehabilitation.
6. If the total duration required differs by more than 1 percent of the available duration calculated in step 2, the rehabilitation length is adjusted using the following formula:

$$\text{If } \left| \frac{(t_i - t_{cw})}{t_{cw}} \right| > 0.01 \text{ and } i < N, \text{ then } L_{i+1} = \frac{(t_i + t_{cw})}{2t_{cw}} L_i \quad (1)$$

where, L_i = rehabilitation length used in iteration i

t_i = time required for rehabilitation length L_i

t_{cw} = time available under the specified construction window

L_{i+1} = optimum rehabilitation length calculated for use in $i+1$ iteration

i, N = current iteration number and maximum number of iterations, respectively

Steps 5 and 6 are repeated until the total duration required is within 1 percent of the available duration or the maximum number of iterations is reached, currently set to 50.

4.8. CONVERGENCE AND SENSITIVITY

Monte Carlo simulation can be set to run for a specified number of simulations or a tolerance criterion can be specified to check for convergence and terminate when convergence is achieved or the specified maximum number of simulations is reached. When the convergence monitoring option is used, a tolerance (ε_i) and a monitoring frequency (n) are specified. *CA4PRS* monitors the convergence of the probability distribution of rehabilitation length (the output) using the following statistics: the mean, standard deviation, and 10, 25, 75 and 90th percentiles. These statistics are calculated at every n simulations and the convergence error is determined as follows:

$$\varepsilon = \frac{\lambda_{i*n} - \lambda_{(i-1)*n}}{\sigma_{(i-1)*n}} \quad (2)$$

where, $i*n = \{\text{mean, standard deviation, or percentiles at 10, 25, 75 and 90 percent}\}$, after $i*n$ iterations, where i is an integer

$(i-1)*n = \{\text{mean, standard deviation, or percentiles at 10, 25, 75 and 90 percent}\}$, after $(i-1)*n$ iterations

$(i-1)*n = \text{standard deviation after } (i-1)*n \text{ iterations}$

The simulation terminates when the maximum error is less than or equal to the specified tolerance, ε_i , or when the number of simulations has reached the maximum specified. *CA4PRS* also provides sensitivity analysis results to aid in identifying critical resources most controlling the rehabilitation production. *CA4PRS* determines the sensitivity of the output rehabilitation production to each of the probabilistic input variables using the Spearman rank order correlation coefficient. *CA4PRS* then produces a sensitivity chart showing the relative significance of the input variables in the output uncertainty. This is useful as a planning strategy to reduce the uncertainty by concentrating on the key input variables that drive the production. This is particularly helpful under incentive/disincentive contracting for early/late completion in evaluating the associated risk.

5. INPUTS AND OUTPUTS INTERFACES

This section provides step-by-step descriptions of the major *CA4PRS* input variables, recommended ranges for each, and analysis examples for the PCC, CSOL, and FDAC rehabilitation strategies. The interpretation of the outputs and reports are summarized at the end of this sections well. Basically, a screenshot of each input and output window is provided and referenced as a numbered figure (e.g., in section 5.1.1, the screen shot of the **Project Details** Input Window is referenced in Figure 12). In each of the description sections that follow, numbers in the circled bullets correspond to circled numbers in the referenced figures.

The input entries illustrated in this report used actual construction productivity and schedule data collected with a validation from Caltrans LLPRS demonstration projects, i.e., the I-15 Devore project for PCC, and the I-710 Long Beach for CSOL and FDAC.

5.1. PCC DETERMINISTIC INPUTS

5.1.1. Project Details Input Window

A screenshot of the PCC **Project Details** input window is provided in Figure 12. Refer to the corresponding circled numbers below and in the figure for information on the input variables.

- ① **Project Identifier:** A brief description of the project, which identifies the uniqueness of the analysis. The project identifier is a global input to appear on the top of the four tab input windows.
- ② **Unit:** *CA4PRS* supports a dual system unit; English (inch and mile) and Metric (millimeter and kilometer). Inputs and outputs are automatically converted between the unit systems for the user in the toggle menu.
- ③ **Post miles:** Beginning and Ending post miles of the rehabilitation.
- ④ **Objective:** The total scope of rehabilitation in terms of lane-km or lane-miles. For instance, the objective of a 5-km stretch with two truck-lanes rehabilitated in each direction is 20 lane-km (5 km x 2 lanes x 2 directions). This objective is divided by the production capability of each closure (lane-km per closure), which is calculated at the end of the analysis, so that the total number of closures needed to finish the whole rehabilitation project is counted as the main output.
- ⑤ **Save:** It is strongly recommended that the user clicks on **Save** after each input change. The MS Access platform sometimes does not take input entries until the **Save** button is clicked.

PCCP Deterministic - PCC Tutorial for I-15 Devore (Your Name)

1 Project Identifier: PCC Tutorial for I-15 Devore (Your Name) 2 Unit: English Metric

Project Details | Scheduling | Resource Profile | Analysis

Project Description: Caltrans District 8 Concrete Demonstration Project

Analyst Name: Your Name Analysis Date: 8 / 1 /2006

Route Name: I-15 Devore, San Bernardino

3 Begin KM: 206.00 End KM: 211.00

4 Objective (lane-km): 17.00

Location: Deveore, San Bernardino, County, CA

Project Notes: 2 truck-lanes reconstruction
Total scope=17 lane-km = 4.3 (2.5 + 1.8) x 2 lanes x 2 directions

5 Save Close

August 2006

Sun	Mon	Tue	Wed	Thu	Fri	Sat
30	31	1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30	31	1	2
3	4	5	6	7	8	9

Today: 8/24/2006

Figure 12: PCC Deterministic Input - Project Details Window

5.1.2. Scheduling Input Window

A screenshot of the PCC **Scheduling** input window is provided in Figure 13. Refer to the corresponding circled numbers below and in the figure for information on the input variables.

- ① **Mobilization** (hours): The duration of mobilization (until the major rehabilitation operations start) and demobilization (when the rehabilitation operations end) is input in hours. The traffic closure is the main activity during the mobilization, and traffic opening and time allocated for concrete curing or AC cooling are the main activities during the demobilization. Usually the mobilization takes about one hour for a short closure (nighttime) and 2 to 3 hours for an extended closure (55-hour weekend or continuous). Mobilization and demobilization durations are subtracted from the closure duration to calculate major operation hours.
- ② **Construction Start Date**: The calendar day of the expected construction is input for information purposes only. However, the calendar data plays some roles in calculating AC cooling time in the *MultiCool* (section 4.4) module to take into account the intensity of the sun radiation.
- ③ **Construction Window**: When this button is clicked, a Construction Window Settings input sub-

window pops, allowing the user to select from four construction windows (closure timing):

- Weekend closure
- Nighttime closure
- Continuous closure with continuous (24-hour) operation
- Continuous closure with daytime shift operation.

The user is able to adjust the duration of the nighttime and weekend closures when he/she changes the start or end time of the closure by clicking the down or up arrow in the time menu. The duration of the continuous closures is directly adjusted with the input of working day numbers (continuous closure/continuous operation) and working hours (continuous closure/shift operation).

- ④ **Sequential Working Method:** PCC paving can only start after the demolition and base activities are completed. This sequence of the operation is required when the activities share the construction access. Input the activity lead-lag time relationships as defined based on linear scheduling of the sequential method (see Figure 11 (b-2)). Typically, the sequential lag time is the finish-to-start relationship, even with a negative number which means the following operation can start before (as early as negatively defined) the precedent operation fully completed.

The screenshot displays the 'PCC Tutorial for I-15 Devore (Your Name)' project in the Scheduling tab. Key fields include:

- Mobilization:** 4.0 Hours
- Demobilization:** 6.0 Hours
- Construction Start Date:** 3 / 1 / 2004
- Lag Times for Sequential Method (Finish to Start):**
 - Demolition to PCCP Installation: 2.0 Hours
 - Demolition to New Base Installation: 1.0 Hours
 - New Base Installation to PCCP Installation: 1.0 Hours
- Lag Times for Concurrent Method (Start to Start):**
 - Demolition to PCCP Installation: 5.0 Hours
 - Demolition to New Base Installation: 9.0 Hours
 - New Base Installation to PCCP Installation: 6.0 Hours

The 'Construction Window Settings' dialog box (labeled 3) provides detailed closure options:

- Weekend Closure:** Start Time on Friday: 10:00 PM, End Time on Monday: 05:00 AM, Available Hours: 55.0
- Nighttime Closure:** Start Time on First Day: 07:00 PM, End Time on Next Day: 05:00 AM, Available Hours per Day: 10.0
- Continuous Closure/Continuous Operation:** Start Time on First Day: 12:00 AM, No. of Continuous Work Days: 3.0, Available Hours per Day: 24.0
- Continuous Closure/Shift Operation:** Daily Start Time: 06:00 AM, No. of Continuous Work Days: 6.0, Available Hours per Day: 16.0

Figure 13: PCC Deterministic Input - Scheduling Windows

- ⑤ **Concurrent Working Method:** Rehabilitation operations can proceed concurrently (in parallel) with its own construction access with some time-intervals (see Figure 11 (b-1)). Input time gaps between each operation define their start-to-start relationships. For example, Demolition to PCCP Installation (about 5 hours) should be defined for the PCC slab replacement only (not including the new base) strategy during the extended closures. Demolition to New Base Installation (about 9 hours) and New Base to PCCP Installation (about 6 hours) should be defined for the PCC reconstruction strategy, including the new base installation, during the extended closures.

5.1.3. Resource Profile Input Window

A screenshot of the PCC **Resource Profile** input window is provided in Figure 14. Refer to the corresponding circled numbers below and in the figure for information on the input variables.

- ① **Dump Truck:** Input details about dump trucks for the hauling of demolition operation include:
- Capacity of Truck: usually 15 to 22 tons of hauling capacity per truckload
 - Trucks per Hour: usually 8 to 12 trucks turned around per hour, depending on the typical cycle-time of the demolition loading
 - Packing Efficiency: usually 0.5 to 0.7 as the efficiency of loose hauling volume compared to the solid volume of demolished pavement, depending on the type of demolition methods. The previous LLPRS case studies indicated that on average the packing efficiency is 0.5 for non-impact demolition (saw cut and slab-lift) of concrete pavement, 0.6 for impact demolition (rubblization and bucket-out) of concrete pavement, 0.7 for milling of AC pavement.
 - Number of Team and Efficiency: Demolition crew number (usually 1 to 3) and its efficiency factor (usually 0.75 to 1.0) considering any chance of interference loss. Each crew will utilize the same resource configuration as input above.
- ② **End Dump Truck** (Base paving): usually 6 to 10 trucks per hour with the capacity of 6 to 10 m³ per truck delivery
- ③ **Batch Plant:** usually 100 to 200 m³ capacity
- ④ **End Dump Truck** (PCC paving): usually 6 to 9 m³ capacity per delivery, depending on the type of truck, with 10 to 15 trucks turned around per hour
- ⑤ **Pavers:** Speed (2 to 3 meter per minute) of paving machine and number of pavers (one in most cases)

Figure 14: PCC Deterministic Input - Resource Profile Window

5.1.4. Analysis Input Window

In this **Analysis** tab input window, multiple analysis alternatives can be selected (checked in the checkbox) in each input group. The total number of analysis outputs is a factorial of checked alternatives. For instance, two alternatives each from: Construction Window, Working Method, Curing Time, and Section Profile groups will produce a total of 16 ($2 \times 2 \times 2 \times 2$) analysis outputs.

A screenshot of the PCC **Analysis** input window is provided in Figure 15. Refer to the corresponding circled numbers below and in the figure for information on the input variables.

- ① **Construction Window:** Any of the four Construction Windows defined in the **Scheduling** tap input window can be included in the analysis for a multi-comparison purpose.
- ② **Working Method:** Any of the Six Working Methods as a combination of Sequential or Concurrent and Single or Double lane rehabilitation, as defined in the previous **Scheduling** input, can be included in the comparison analysis. When the “INFO?” icon is clicked, the Construction Plan sub-window pops up to illustrate the lane closure scheme for each of the six Working Methods alternating with a dynamic image link (Figure 16).

- ③ **Curing Time:** Different concrete curing times (depending on the mix design), measured from after placement to opening construction to traffic, are selected in this input. The User Define option is available in case the project uses a concrete mix other than the of 4, 8, and 12-hour curing time mixes of the three rapid strength concrete options in the built-in menu.
- ④ **Section Profile:** The changes of concrete pavement cross section are defined in this input. When the 'INFO?' icon is clicked, more graphical information describing typical cross section changes for California LLPRS is displayed in the sub-window (Figure 16).

In the case of the 203-mm (8 inch) alternative, only the existing slab is replaced with a new slab of the same thickness, whereas the 254-mm (10 inch) and 305-mm (12 inch) sections are assumed to rebuild the new base of 150 mm (6 inch) thickness as well. If these three typical cross section changes are not applicable for the project, the user can define a pavement cross section change in the user defined option with the input of PCCP (slab) and Treated Base thicknesses.

Additional demolition is available for a situation where the new pavement surface level (longitude profile) is not the same as the existing one. This input option is also useful when additional demolition is required to provide more clearance under highway overpasses. A negative (-) depth is used when, after the rehabilitation, the new surface level is higher than the existing profile.

- ⑤ **Lane Widths:** The width of newly rehabilitated two truck lanes are defined in this input. A California LLPRS practice is to implement a widened (4.37m = 14') outer truck lane to prevent cracking of the slab with wider distribution of heavy truck loads.
- ⑥ **Analyze:** When the user clicks the **Analyze** button all inputs are completed in the above four tab input windows. Analysis outputs pop up in an individual output widow for each alternative scenario checked in the **Analysis** input window.
- ⑦ **Compare:** When the user checks multiple options in each category in the **Analysis** window, the number of output windows may be too large for effective comparison of all the analyzed scenarios at once. To avoid this inconvenience, the user may click the **Compare** button to generate a simplified comparison table.

Project Identifier: Unit: ☐ English ☒ Metric

Project Details | **Scheduling** | Resource Profile | Analysis

Construction Window

☒ Weekend Closure

☐ Nighttime Closure

☒ Continuous Closure/Continuous Operation

☐ Continuous Closure/Shift Operation

Curing Time

☐ 4-Hours

☐ 8-Hours

☒ 12-Hours

☐ User Defined Hours

Section Profile

☒ 203 mm (8 inches)

☐ 254 mm (10 inches)

☒ 305 mm (12 inches)

User Defined

☐ User Defined

PCCP (mm):

Treated Base (mm):

Additional Demolition

☐ Additional Demolition

Depth (mm):

Working Method

☐ Sequential Single Lane (T1)

☐ Sequential Single Lane (T2)

☐ Sequential Double Lane (T1+T2)

☐ Concurrent Single Lane (T1)

☐ Concurrent Single Lane (T2)

☒ Concurrent Double Lane (T1+T2)

Lane Widths

☒ T1 Width (m): T2 Width (m):

Figure 15: PCC Deterministic Input - Analysis Window

Construction Plan

☒ Sequential Single Lane (T1)

☐ Sequential Single Lane (T2)

☐ Sequential Double Lane (T1+T2)

☐ Concurrent Single Lane (T1)

☐ Concurrent Single Lane (T2)

☐ Concurrent Double Lane (T1+T2)

Construction Plan

S1 P1 P2 T1 T2 S2

Open Access Paving

Section Profile

Existing Profile		New Profile	
CONCRETE	203mm (8")	CONCRETE	203mm (8")
CTB	102mm (4")	CTB	102mm (4")
AB	305mm (12")	AB	305mm (12")
SG		SG	

(a) 203 mm Concrete Slab

Existing Profile		New Profile	
CONCRETE	203mm (8")	CONCRETE	254mm (10")
CTB	102mm (4")	CTB	102mm (4")
AB	305mm (12")	AB	203mm (8")
SG		SG	

(b) 254 mm Concrete Slab

Existing Profile		New Profile	
CONCRETE	203mm (8")	CONCRETE	305mm (12")
CTB	102mm (4")	CTB	102mm (4")
AB	305mm (12")	AB	102mm (4")
SG		SG	

(c) 305 mm Concrete Slab

Figure 16: PCC Analysis Information - Construction Methods and Section Profile

5.2. PCC DETERMINISTIC OUTPUTS

5.2.1. Outputs and Reports

The analysis outputs are displayed on the screen or filed in the report. The outputs are grouped into three categories in the output tab windows: **Production Details**, **Production Chart**, and **Gant Charts** (under development). In the **Production Details** output, major inputs are registered at the top followed by the main output of the production and schedule estimates. A screenshot of the Outputs and Reports window is provided in Figure 17. Refer to the corresponding circled numbers below and in the figure for information on the output results.

- ① **Maximum Possible:** As highlighted in yellow, this provides the estimate of the maximum possible production in terms of the centerline- km.
- ② **Total Closures:** The total number of closures (construction windows) is displayed under the Maximum Possible and calculated by dividing the objective (project scope) by the Maximum Possible production.

Additional output information, such as material volumes to be treated per closure, constraining resource based on linear scheduling, and demolition and paving operation hours, is provided at the bottom of the output summary table.

- ③ **Constraining Resource:** Based on the linear scheduling technique, the analysis algorithm points out which resource constrains the maximum rehabilitation production. In this case the output shows that the dump truck for demolition hauling is identified as the critical (constraining) resource, so the total number of trucks allocated in the input (in this case 10) will be fully utilized.
- ④ Other non-constrained resources have redundancy. For example, only about 13 (12.8) End Dump Trucks for concrete delivery will be utilized among the assumed 15 trucks to match up with the constraining demolition dump trucks.

Production Charts in the output display Linear Scheduling of the major rehabilitation operations, which indicate progress (centerline-km) in the vertical axis as a function of timeline in the horizontal axis during the closure (see Figure 18).

The outputs are outlined in a report format when the **Report** button at the bottom of the output screen is clicked. The report file displayed on the screen can be printed from the main menu (**File** => **Print**) or saved electronically in a PDF format (see Figure 19).

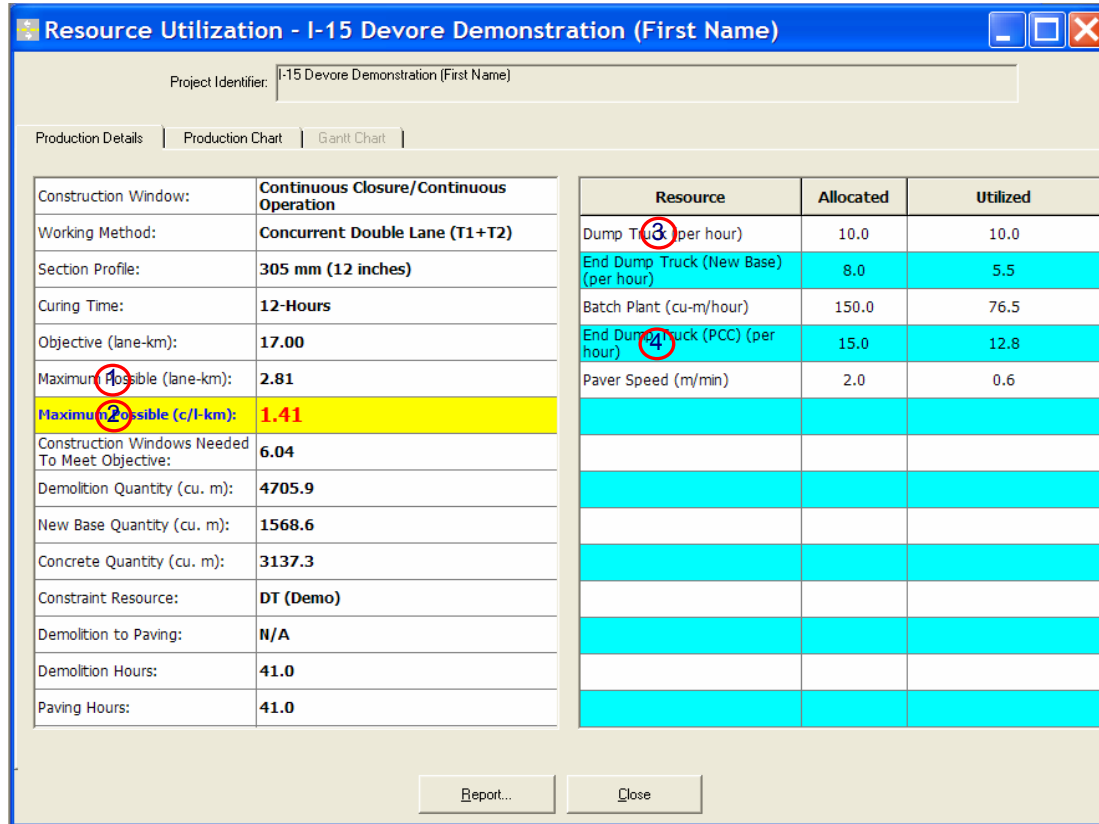


Figure 17: PCC Deterministic Output - Production Details

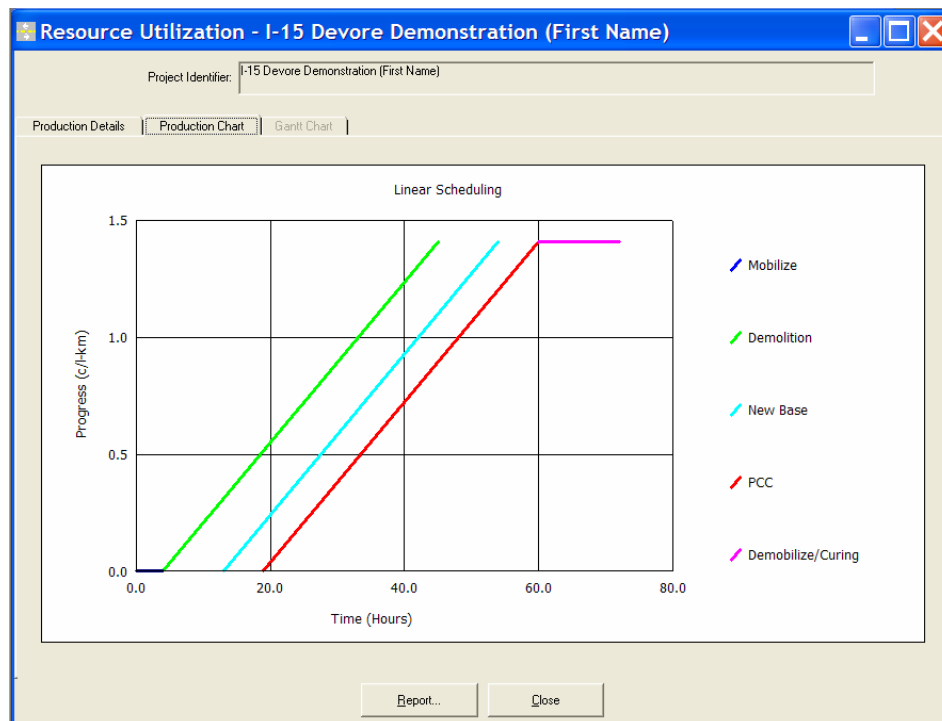


Figure 18: PCC Deterministic Output -Production Chart with Linear Scheduling

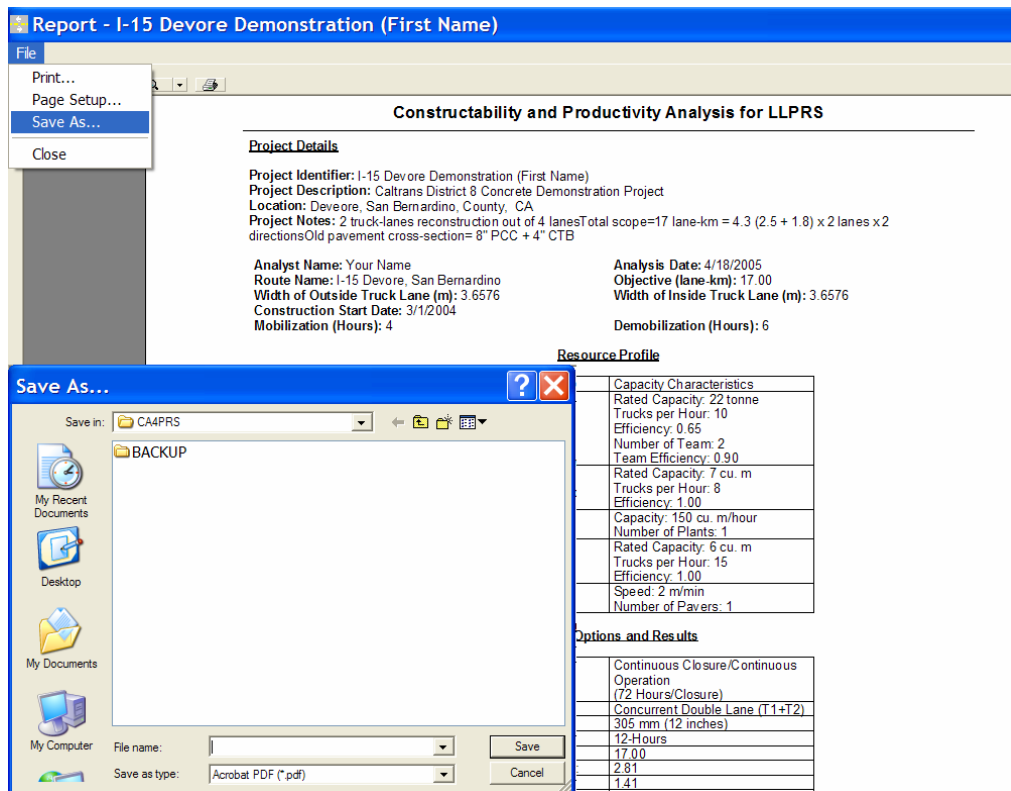


Figure 19: PCC Analysis Output (Report and Save as a PDF file)

5.2.2. Multiple Analysis: Scenario Comparison

As *CA4PRS* supports a dual units system, the maximum production per closure (centerline-km) in the output in the different system unit can be retrieved instantly when the user switches one unit to the other in the Unit input group at the top (Figure 20). The production output for the analysis situation of the widened (4.3 m) truck-lane reconstruction scenario is displayed when the user changes the lane width (T2) (Figure 21).

CA4PRS has a user-friendly feature to make multiple comparison analyses with multiple output displays at once. For example, the user can compare the production schedule between weekend (55-hour) and continuous (72-hour) weekday closures with respect to the Construction Window alternatives. When the user checks the two alternatives in the **Analysis** input window and clicks the **Analyze** button, two analysis output windows pop up so that the user can arrange them side by side on the screen to compare the productions and schedules (

Figure 22 and Figure 23).

Similarly, when the user checks 203 mm (8 inch) and 305 mm (12 inch) slabs and clicks **Analyze** to compare two alternatives of the pavement section profile change, two analysis results pop up in its own output window (Figure 24 and

Figure 25). When the user checks sequential single lane (usually half closure of the construction roadbed) and concurrent double lane (full closure of the construction roadbed) to compare the production

difference between the working method in conjunction with the lane closure tactics, the analysis results are generated in the two output windows (Figure 26 and Figure 27). Comparing the production difference (consequently the needed closure numbers) between the two alternatives of the 12-hour and 24-hour (user defined) mix in terms of concrete curing time, two outputs are arranged side by side same as they were for previous comparison cases (Figure 28 and Figure 29).

In addition to producing multiple analysis results in its own output window, *CA4PRS* has a better out arrangement for a multi-scenario comparison, especially when the user has a number of scenarios as a combination of the comparison criteria. When the user clicks the **Compare** button with multiple analysis alternatives, the outputs are summarized in a hierarchical manner starting with the construction window, then the cross section profile, then the rehabilitation sequence, etc. (Figure 30 and Figure 31). This feature is useful for comparing the rehabilitation productions and closure numbers in the report.

5.3. PCC PROBABILISTIC ANALYSIS INPUTS

The probabilistic analysis input starts with the *CA4PRS* main menu: **File => New (or Open) => PCCP (or FDAC or CSOL) => Probabilistic**. Although the user relies on the default condition, such as Sampling Scheme and Iteration for most probabilistic analysis cases, the settings including the iteration number (default is 4,000) and the iteration tolerance (default is 1 percent) for the Monte Carlo simulation, which can be adjusted in the main menu: **Options => Simulation Settings** (Figure 32).

The basic configuration of the probabilistic analysis on the four tab input windows is more or less the same as the deterministic analysis. The biggest difference is that the same inputs in the probabilistic analysis have a graph icon next to a check box in the **Scheduling** (① in Figure 33) and **Resource Profile** (② in Figure 34) input tab windows.

When the check box is selected to assign the input as a random variable and the graph icon is clicked, a sub-window of Define Probability Input pops up. The user can select the best type of Probabilistic Function for that particular probabilistic input variable in the library by clicking the down-arrow button, including: Uniform, Normal, Log Normal, Triangular, Beta, etc. The user is asked to further define the Probability Function selected with such inputs as the mean and the standard deviation for Normal distribution, and minimum, most likely, and maximum for the Triangular distribution.

Project Identifier: PCC Tutorial for I-15 Devore (Your Name) Unit: English Metric

Project Details | Scheduling | Resource Profile | Analysis |

Construction Window

- ☐ Weekend Closure
- ☐ Nighttime Closure
- ☒ Continuous Closure/Continuous Operation
- ☐ Continuous Closure/Shift Operation

Curing Time

- ☐ 4-Hours
- ☐ 8-Hours
- ☒ 12-Hours
- ☐ User Defined 24.0 Hours

Section Profile

- ☐ 203 mm (8 inches)
- ☐ 254 mm (10 inches)
- ☒ 305 mm (12 inches)

User Defined

☐ User Defined PCCP (in): 11.4 Treated Base (in): 6.0

Additional Demolition

☐ Additional Demolition Depth (in): 3.9

Working Method

- ☐ Sequential Single Lane (T1)
- ☐ Sequential Single Lane (T2)
- ☐ Sequential Double Lane (T1+T2)
- ☐ Concurrent Single Lane (T1)
- ☐ Concurrent Single Lane (T2)
- ☒ Concurrent Double Lane (T1+T2)

Analyze... Compare...

Lane Widths

T1 Width (ft): 12.0 T2 Width (ft): 12.0

Production Details | Production Chart | Gantt Chart |

Resource	Allocated	Utilized
Demolition Hauling Truck (per hour per team)	10.0	10.0
Base Delivery Truck (per hour)	8.0	5.5
Batch Plant (cu-yd/hour)	196.2	100.1
Concrete Delivery Truck (per hour)	15.0	12.8
Paver Speed (ft/min)	6.6	1.9

Construction Window: Continuous Closure/Continuous Operation (72 Hours/Closure)

Working Method: Concurrent Double Lane (T1+T2)

Section Profile: 305 mm (12 inches)

Curing Time: 12-Hours

Objective (lane-miles): 10.56

Maximum Possible (lane-miles): 1.75

Maximum Possible (c/f-miles): 0.87

Construction Windows Needed To Meet Objective: 6.04

Demolition Quantity (cu. yd): 6155.1

New Base Quantity (cu. yd): 2051.7

Concrete Quantity (cu. yd): 4103.4

Constraint Resource: Demolition Hauling Truck

Figure 20: Analysis Unit Change (from Metric to English) in Input and Output

Project Identifier: PCC Tutorial for I-15 Devore (Your Name) Unit: English Metric

Project Details | Scheduling | Resource Profile | Analysis |

Construction Window

- ☐ Weekend Closure
- ☐ Nighttime Closure
- ☒ Continuous Closure/Continuous Operation
- ☐ Continuous Closure/Shift Operation

Curing Time

- ☐ 4-Hours
- ☐ 8-Hours
- ☒ 12-Hours
- ☐ User Defined 24.0 Hours

Section Profile

- ☐ 203 mm (8 inches)
- ☐ 254 mm (10 inches)
- ☒ 305 mm (12 inches)

User Defined

☐ User Defined PCCP (mm): 290.0 Treated Base (mm): 152.4

Additional Demolition

☐ Additional Demolition Depth (mm): 100.0

Working Method

- ☐ Sequential Single Lane (T1)
- ☐ Sequential Single Lane (T2)
- ☐ Sequential Double Lane (T1+T2)
- ☐ Concurrent Single Lane (T1)
- ☐ Concurrent Single Lane (T2)
- ☒ Concurrent Double Lane (T1+T2)

Analyze... Compare...

Lane Widths

T1 Width (m): 3.7 T2 Width (m): 4.3

Production Details | Production Chart | Gantt Chart |

Resource	Allocated	Utilized
Demolition Hauling Truck (per hour per team)	10.0	10.0
Base Delivery Truck (per hour)	8.0	5.5
Batch Plant (cu-m/hour)	150.0	76.5
Concrete Delivery Truck (per hour)	15.0	12.8
Paver Speed (m/min)	2.0	0.5

Construction Window: Continuous Closure/Continuous Operation

Working Method: Concurrent Double Lane (T1+T2)

Section Profile: 305 mm (12 inches)

Curing Time: 12-Hours

Objective (lane-km): 17.00

Maximum Possible (lane-km): 2.60

Maximum Possible (c/f-km): 1.30

Construction Windows Needed To Meet Objective: 6.54

Demolition Quantity (cu. m): 4705.9

Figure 21: PCC Input and Output for Widened (14') Truck-lane Scenario

Project Identifier:

Unit: ☐ English ☒ Metric

Project Details | Scheduling | Resource Profile | Analysis

Construction Window

☒ Weekend Closure

☐ Nighttime Closure

☒ Continuous Closure/Continuous Operation

☐ Continuous Closure/Shift Operation

Curing Time

☐ 4-Hours

☐ 8-Hours

☒ 12-Hours

☐ User Defined Hours

Section Profile

☐ 203 mm (8 inches)

☐ 254 mm (10 inches)

☒ 305 mm (12 inches)

User Defined

☐ User Defined

PCCP (mm):

Treated Base (mm):

Additional Demolition

☐ Additional Demolition

Depth (mm):

Working Method

☐ Sequential Single Lane (T1)

☐ Sequential Single Lane (T2)

☐ Sequential Double Lane (T1+T2)

☐ Concurrent Single Lane (T1)

☐ Concurrent Single Lane (T2)

☒ Concurrent Double Lane (T1+T2)

Lane Widths

T1 Width (m):

T2 Width (m):

Analyze...

Compare...

Figure 22: PCC Input for Scenarios Comparison-Weekend vs. Continuous Closures

Resource Utilization - PCC Tutorial for I-15 Devore (Your Name)		Resource Utilization - PCC Tutorial for I-15 Devore (Your Name)	
Project Identifier: <input type="text" value="PCC Tutorial for I-15 Devore (Your Name)"/>		Project Identifier: <input type="text" value="PCC Tutorial for I-15 Devore (Your Name)"/>	
Production Details Production Chart Gantt Chart		Production Details Production Chart Gantt Chart	
Construction Window:	Continuous Closure/Continuous Operation (72 Hours/Closure)	Construction Window:	Weekend Closure (55 Hours/Weekend)
Working Method:	Concurrent Double Lane (T1+T2)	Working Method:	Concurrent Double Lane (T1+T2)
Section Profile:	305 mm (12 inches)	Section Profile:	305 mm (12 inches)
Curing Time:	12-Hours	Curing Time:	12-Hours
Objective (lane-km):	17.00	Objective (lane-km):	17.00
Maximum Possible (lane-km):	2.81	Maximum Possible (lane-km):	1.65
Maximum Possible (c/l-km):	1.41	Maximum Possible (c/l-km):	0.82
Construction Windows Needed To Meet Objective:	6.04	Construction Windows Needed To Meet Objective:	10.32
Demolition Quantity (cu. m):	4705.9	Demolition Quantity (cu. m):	2754.7
New Base Quantity (cu. m):	1568.6	New Base Quantity (cu. m):	918.2
Concrete Quantity (cu. m):	3137.3	Concrete Quantity (cu. m):	1836.5
Constraint Resource:	Demolition Hauling Truck	Constraint Resource:	Demolition Hauling Truck
Demolition to Paving:	N/A	Demolition to Paving:	N/A
Demolition Hours:	41.0	Demolition Hours:	24.0
Paving Hours:	41.0	Paving Hours:	24.0
Report...		Report... Close	

Figure 23: PCC Output for Two Scenarios-Weekend vs. Continuous Closure

Project Identifier:

Unit: ☐ English ☒ Metric

Project Details | Scheduling | Resource Profile | Analysis

Construction Window

☐ Weekend Closure

☐ Nighttime Closure

☒ Continuous Closure/Continuous Operation

☐ Continuous Closure/Shift Operation

Curing Time

☐ 4-Hours

☐ 8-Hours

☒ 12-Hours

☐ User Defined Hours

Section Profile

☒ 203 mm (8 inches)

☐ 254 mm (10 inches)

☒ 305 mm (12 inches)

User Defined

☐ User Defined

PCCP (mm):

Treated Base (mm):

Additional Demolition

☐ Additional Demolition

Depth (mm):

Lane Widths

T1 Width (m): T2 Width (m):

Working Method

☐ Sequential Single Lane (T1)

☐ Sequential Single Lane (T2)

☐ Sequential Double Lane (T1+T2)

☐ Concurrent Single Lane (T1)

☐ Concurrent Single Lane (T2)

☒ Concurrent Double Lane (T1+T2)

Analyze...

Compare...

Save Close

Figure 24: PCC Input for Two Scenarios - 203mm vs. 305mm Slab

Project Identifier: <input type="text" value="PCC Tutorial for I-15 Devore (Your Name)"/>	Project Identifier: <input type="text" value="PCC Tutorial for I-15 Devore (Your Name)"/>																																																												
Production Details Production Chart Gantt Chart	Production Details Production Chart Gantt Chart																																																												
<table> <tr> <td>Construction Window:</td><td>Continuous Closure/Continuous Operation (72 Hours/Closure)</td></tr> <tr> <td>Working Method:</td><td>Concurrent Double Lane (T1+T2)</td></tr> <tr> <td>Section Profile:</td><td>305 mm (12 inches)</td></tr> <tr> <td>Curing Time:</td><td>12-Hours</td></tr> <tr> <td>Objective (lane-km):</td><td>17.00</td></tr> <tr> <td>Maximum Possible (lane-km):</td><td>2.81</td></tr> <tr> <td>Maximum Possible (c/l-km):</td><td>1.41</td></tr> <tr> <td>Construction Windows Needed To Meet Objective:</td><td>6.04</td></tr> <tr> <td>Demolition Quantity (cu. m):</td><td>4705.9</td></tr> <tr> <td>New Base Quantity (cu. m):</td><td>1568.6</td></tr> <tr> <td>Concrete Quantity (cu. m):</td><td>3137.3</td></tr> <tr> <td>Constraint Resource:</td><td>Demolition Hauling Truck</td></tr> <tr> <td>Demolition to Paving:</td><td>N/A</td></tr> <tr> <td>Demolition Hours:</td><td>41.0</td></tr> <tr> <td>Paving Hours:</td><td>41.0</td></tr> </table>	Construction Window:	Continuous Closure/Continuous Operation (72 Hours/Closure)	Working Method:	Concurrent Double Lane (T1+T2)	Section Profile:	305 mm (12 inches)	Curing Time:	12-Hours	Objective (lane-km):	17.00	Maximum Possible (lane-km):	2.81	Maximum Possible (c/l-km):	1.41	Construction Windows Needed To Meet Objective:	6.04	Demolition Quantity (cu. m):	4705.9	New Base Quantity (cu. m):	1568.6	Concrete Quantity (cu. m):	3137.3	Constraint Resource:	Demolition Hauling Truck	Demolition to Paving:	N/A	Demolition Hours:	41.0	Paving Hours:	41.0	<table> <tr> <td>Construction Window:</td><td>Continuous Closure/Continuous Operation (72 Hours/Closure)</td></tr> <tr> <td>Working Method:</td><td>Concurrent Double Lane (T1+T2)</td></tr> <tr> <td>Section Profile:</td><td>203 mm (8 inches)</td></tr> <tr> <td>Curing Time:</td><td>12-Hours</td></tr> <tr> <td>Objective (lane-km):</td><td>17.00</td></tr> <tr> <td>Maximum Possible (lane-km):</td><td>6.18</td></tr> <tr> <td>Maximum Possible (c/l-km):</td><td>3.09</td></tr> <tr> <td>Construction Windows Needed To Meet Objective:</td><td>2.75</td></tr> <tr> <td>Demolition Quantity (cu. m):</td><td>4590.0</td></tr> <tr> <td>New Base Quantity (cu. m):</td><td>0.0</td></tr> <tr> <td>Concrete Quantity (cu. m):</td><td>4590.0</td></tr> <tr> <td>Constraint Resource:</td><td>Concrete Delivery Truck</td></tr> <tr> <td>Demolition to Paving:</td><td>N/A</td></tr> <tr> <td>Demolition Hours:</td><td>51.0</td></tr> <tr> <td>Paving Hours:</td><td>51.0</td></tr> </table>	Construction Window:	Continuous Closure/Continuous Operation (72 Hours/Closure)	Working Method:	Concurrent Double Lane (T1+T2)	Section Profile:	203 mm (8 inches)	Curing Time:	12-Hours	Objective (lane-km):	17.00	Maximum Possible (lane-km):	6.18	Maximum Possible (c/l-km):	3.09	Construction Windows Needed To Meet Objective:	2.75	Demolition Quantity (cu. m):	4590.0	New Base Quantity (cu. m):	0.0	Concrete Quantity (cu. m):	4590.0	Constraint Resource:	Concrete Delivery Truck	Demolition to Paving:	N/A	Demolition Hours:	51.0	Paving Hours:	51.0
Construction Window:	Continuous Closure/Continuous Operation (72 Hours/Closure)																																																												
Working Method:	Concurrent Double Lane (T1+T2)																																																												
Section Profile:	305 mm (12 inches)																																																												
Curing Time:	12-Hours																																																												
Objective (lane-km):	17.00																																																												
Maximum Possible (lane-km):	2.81																																																												
Maximum Possible (c/l-km):	1.41																																																												
Construction Windows Needed To Meet Objective:	6.04																																																												
Demolition Quantity (cu. m):	4705.9																																																												
New Base Quantity (cu. m):	1568.6																																																												
Concrete Quantity (cu. m):	3137.3																																																												
Constraint Resource:	Demolition Hauling Truck																																																												
Demolition to Paving:	N/A																																																												
Demolition Hours:	41.0																																																												
Paving Hours:	41.0																																																												
Construction Window:	Continuous Closure/Continuous Operation (72 Hours/Closure)																																																												
Working Method:	Concurrent Double Lane (T1+T2)																																																												
Section Profile:	203 mm (8 inches)																																																												
Curing Time:	12-Hours																																																												
Objective (lane-km):	17.00																																																												
Maximum Possible (lane-km):	6.18																																																												
Maximum Possible (c/l-km):	3.09																																																												
Construction Windows Needed To Meet Objective:	2.75																																																												
Demolition Quantity (cu. m):	4590.0																																																												
New Base Quantity (cu. m):	0.0																																																												
Concrete Quantity (cu. m):	4590.0																																																												
Constraint Resource:	Concrete Delivery Truck																																																												
Demolition to Paving:	N/A																																																												
Demolition Hours:	51.0																																																												
Paving Hours:	51.0																																																												
Report...	Report... Close																																																												

Figure 25: PCC Output for Two Scenarios- 203mm vs. 305mm Slab

Project Identifier:

PCC Tutorial for I-15 Devore (Your Name)

Unit

☐ English
☒ Metric

Project Details

Scheduling

Resource Profile

Analysis

Construction Window

☐ Weekend Closure
☐ Nighttime Closure
☒ Continuous Closure/Continuous Operation
☐ Continuous Closure/Shift Operation

Section Profile

☐ 203 mm (8 inches)
☐ 254 mm (10 inches)
☒ 305 mm (12 inches)

User Defined

☐ User Defined

PCCP (mm):

290.0

Treated Base (mm):

152.4

Additional Demolition

☐ Additional Demolition

Depth (mm):

100.0

Lane Widths

T1 Width (m):

3.7

T2 Width (m):

3.7

Curing Time

☐ 4-Hours
☐ 8-Hours
☒ 12-Hours
☐ User Defined

24.0

Hours

Working Method

☒ Sequential Single Lane (T1)
☐ Sequential Single Lane (T2)
☐ Sequential Double Lane (T1+T2)
☒ Concurrent Single Lane (T1)
☐ Concurrent Single Lane (T2)
☐ Concurrent Double Lane (T1+T2)

Analyze...

Compare...

Save

Close

Figure 26: PCC Input for the Sequential Method

[illegible]

Figure 27: PCC Output for the Sequential Method

Project Identifier:

Unit: ☐ English ☒ Metric

Project Details | Scheduling | Resource Profile | Analysis

Construction Window

☐ Weekend Closure

☐ Nighttime Closure

☒ Continuous Closure/Continuous Operation

☐ Continuous Closure/Shift Operation

Curing Time

☐ 4-Hours

☐ 8-Hours

☒ 12-Hours

☒ User Defined Hours

Section Profile

☐ 203 mm (8 inches)

☐ 254 mm (10 inches)

☒ 305 mm (12 inches)

User Defined

☐ User Defined

PCCP (mm):

Treated Base (mm):

Working Method

☐ Sequential Single Lane (T1)

☐ Sequential Single Lane (T2)

☐ Sequential Double Lane (T1+T2)

☐ Concurrent Single Lane (T1)

☐ Concurrent Single Lane (T2)

☒ Concurrent Double Lane (T1+T2)

Additional Demolition

☐ Additional Demolition

Depth (mm):

Lane Widths

T1 Width (m):

T2 Width (m):

Analyze...

Compare...

Save Close

Figure 28: PCC Input for Two Scenarios - 12 vs. 24 hours Curing-time

Resource Utilization - I-15 Devore		Resource Utilization - I-15 Devore Demonstration (First ...		
Project Identifier: I-15 Devore Demonstration (First Name)		Project Identifier: I-15 Devore Demonstration (First Name)		
Production Details Production Chart Gantt Chart		Production Details Production Chart Gantt Chart		
Construction Window:	Continuous Closure/Continuous Operation	Construction Window:	Continuous Closure/Continuous Operation	
Working Method:	Concurrent Double Lane (T1+T2)	Working Method:	Concurrent Double Lane (T1+T2)	
Section Profile:	305 mm (12 inches)	Section Profile:	305 mm (12 inches)	
Curing Time:	24 Hours	Curing Time:	12-Hours	
Objective (lane-km):	17.00	Objective (lane-km):	17.00	
Maximum Possible (lane-km):	1.99	Maximum Possible (lane-km):	2.81	
Maximum Possible (c/l-km):	1.00	Maximum Possible (c/l-km):	1.41	
Construction Windows Needed To Meet Objective:	8.54	Construction Windows Needed To Meet Objective:	6.04	
Demolition Quantity (cu. m):	3328.6	Demolition Quantity (cu. m):	4705.9	
New Base Quantity (cu. m):	1109.5	New Base Quantity (cu. m):	1568.6	
Concrete Quantity (cu. m):	2219.0	Concrete Quantity (cu. m):	3137.3	
Constraint Resource:	DT (Demo)	Constraint Resource:	DT (Demo)	
Demolition to Paving:	N/A	Demolition to Paving:	N/A	
Demolition Hours:	29.0	Demolition Hours:	41.0	
Report...		Report... Close		

Resource	Allocated	Utilized
Dump Truck (per hour)	10.0	10.0
End Dump Truck (New Base) (per hour)	8.0	5.5
Batch Plant (cu-m/hour)	150.0	76.5
End Dump Truck (PCC) (per hour)	15.0	12.8
Paver Speed (m/min)	2.0	0.6

Figure 29: PCC Output for Two Scenarios-24 vs. 12 hours Curing-time

Project Identifier:

Unit: ☐ English ☒ Metric

Project Details | Scheduling | Resource Profile | Analysis

Construction Window

☒ Weekend Closure

☐ Nighttime Closure

☒ Continuous Closure/Continuous Operation

☐ Continuous Closure/Shift Operation

Curing Time

☒ 4-Hours

☐ 8-Hours

☒ 12-Hours

☐ User Defined Hours

Section Profile

☒ 203 mm (8 inches)

☐ 254 mm (10 inches)

☒ 305 mm (12 inches)

User Defined

☐ User Defined

PCCP (mm):

Treated Base (mm):

Additional Demolition

☐ Additional Demolition

Depth (mm):

Working Method

☒ Sequential Single Lane (T1)

☐ Sequential Single Lane (T2)

☐ Sequential Double Lane (T1+T2)

☐ Concurrent Single Lane (T1)

☐ Concurrent Single Lane (T2)

☒ Concurrent Double Lane (T1+T2)

Lane Widths

T1 Width (m): T2 Width (m):

Figure 30: PCC Input to Compare Multiple Alternative Scenarios

Construction Window	Section Profile	Curing Time	Working Method	Maximum Possible (lane-km)	Constraint Resource	Construction Windows	Total Working Hours
Weekend Closure (55 Hours/Weekend)	203 mm (8 inches)	4-Hours	Sequential Single Lane (T1)	3.04	Demolition Hauling Truck, Paver	5.59	307.7
			Concurrent Double Lane	4.84	EDT(PCC)	3.51	193.0
	305 mm (12 inches)	12-Hours	Sequential Single Lane (T1)	2.63	Demolition Hauling Truck, Paver	6.46	355.0
			Concurrent Double Lane	4.12	EDT(PCC)	4.13	227.1
		4-Hours	Sequential Single Lane (T1)	1.67	Demolition Hauling Truck, Concrete	10.18	560.1
			Concurrent Double Lane	2.06	Demolition Hauling Truck	8.26	454.1
Continuous Closure/Continuous Operation (72 Hours/Closure)	203 mm (8 inches)	12-Hours	Sequential Single Lane (T1)	1.45	EDT(PCC)	11.75	646.3
			Concurrent Double Lane	1.65	Demolition Hauling Truck	10.32	567.6
	305 mm (12 inches)	4-Hours	Sequential Single Lane (T1)	4.19	Demolition Hauling Truck, Paver	4.06	292.4
			Concurrent Double Lane	6.90		2.46	177.3
		12-Hours	Sequential Single Lane (T1)	3.78	Demolition Hauling Truck, Paver	4.50	323.7
			Concurrent Double Lane	6.18	EDT(PCC)	2.75	198.2
	305 mm (12 inches)	4-Hours	Sequential Single Lane (T1)	2.30	Demolition Hauling Truck, Concrete	7.39	532.2
			Concurrent Double Lane	3.23	Demolition Hauling Truck	5.27	379.4
		12-Hours	Sequential Single Lane (T1)	2.08	EDT(PCC)	8.18	589.2

Color Coding Legend

Objective can be accomplished in one Construction Window

Objective requires more than one Construction Window

Not a feasible Construction Window

Figure 31: PCC Analysis Output Comparing Multiple Scenarios

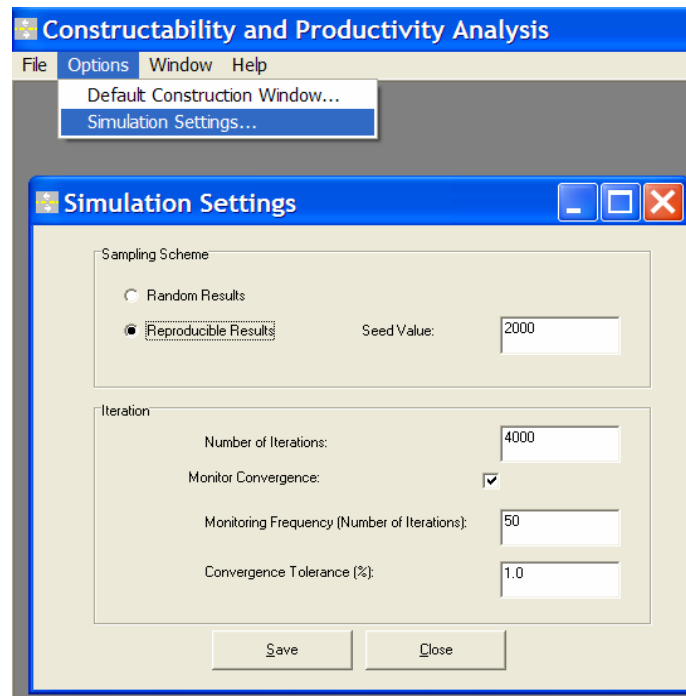


Figure 32: Simulation Setting for Probabilistic Analysis

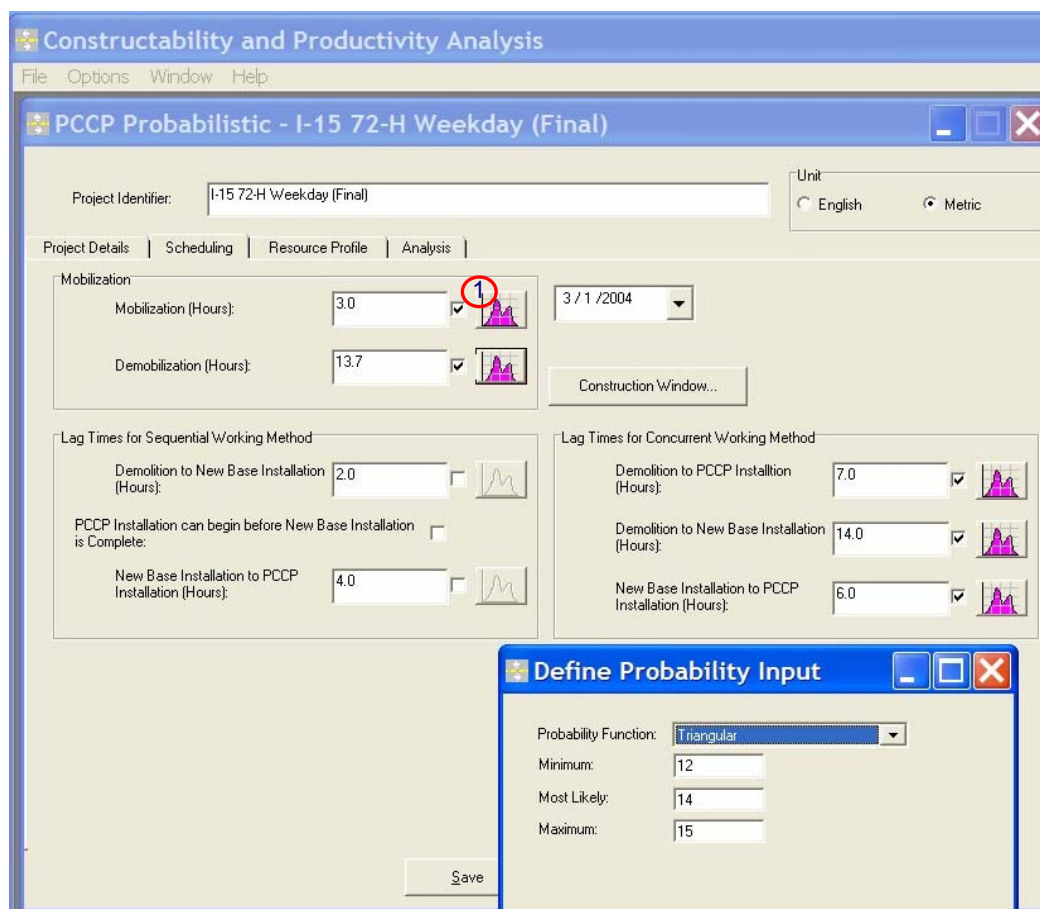


Figure 33: PCC Probabilistic Input - Scheduling Window

5.4. PCC PROBABILISTIC ANALYSIS OUTPUTS

Once the probabilistic inputs are completed, the user can start the simulation by clicking **Analyze** in the **Analysis** window. The simulation sub-window pops up with a summary of probabilistic inputs to start the iteration when the user clicks **Simulate** (③ in Figure 36). **Production Distribution Chart** is the main output of the probabilistic analysis along with (④ in Figure 37) along with **Production Details** of which output format is similar to the deterministic one. **Production Distribution Chart** indicates the relative frequency of the production as the accumulative distribution output combining the probabilistic input distributions. In **Production Distribution Chart**, a range of maximum possible production with one standard deviation is marked at the bottom: low boundary (the worst production scenario), upper boundary (the best production scenario), and the mean (the most likely production scenario).

One other advantage of the probabilistic analysis is that it permits the user to see in the sensitivity chart the relative contribution of the probabilistic input variables to the rehabilitation production as a whole. The **Sensitivity Chart**, commonly called a “tornado chart”, represents relative contributions of each probabilistic input variable to the production with a Spearman Correlation Coefficient (⑤ in Figure 37). The longer the horizontal bar, the greater the impact is on the production. One example of the utilization of the **Sensitivity Chart** is that the planner and contractor should pay more attention to the variables on the top of the chart as these variables are likely to control the maximum rehabilitation goal (production).

5.5. CSOL ANALYSIS INPUTS

The basic input variables and output outline for the CSOL analysis are similar to those in the PCC analysis, especially the **Project Details** and **Schedule** input windows (Figure 38 and Figure 39).

5.5.1. CSOL Resource Profile Input Window

A screenshot of the CSOL **Resources Profile** Input Window is provided in Figure 40. Refer to the corresponding circled numbers below and in the figure for information on the input variable.

- ① **Batch Plant**: usually 300 to 500 tonne per hour capacity
- ② **Semi-bottom Trucks (AC)**: usually 15 to 24 tonne capacity truck per delivery, depending on the truck type, with 10 to 20 trucks per hour with turn around decided by the type of discharge
- ③ **Paver**: Non-paving travel speed of the paver, usually 30 km per hour. AC paving is assumed to proceed uni-direction, in which non-paving hours are calculated for the paving crew to travel back to the starting point. This paver’s idle time for travel is added up with multiple pools of AC paving, depending on the number of lanes and layers, and is subtracted for the main paving operation hours.

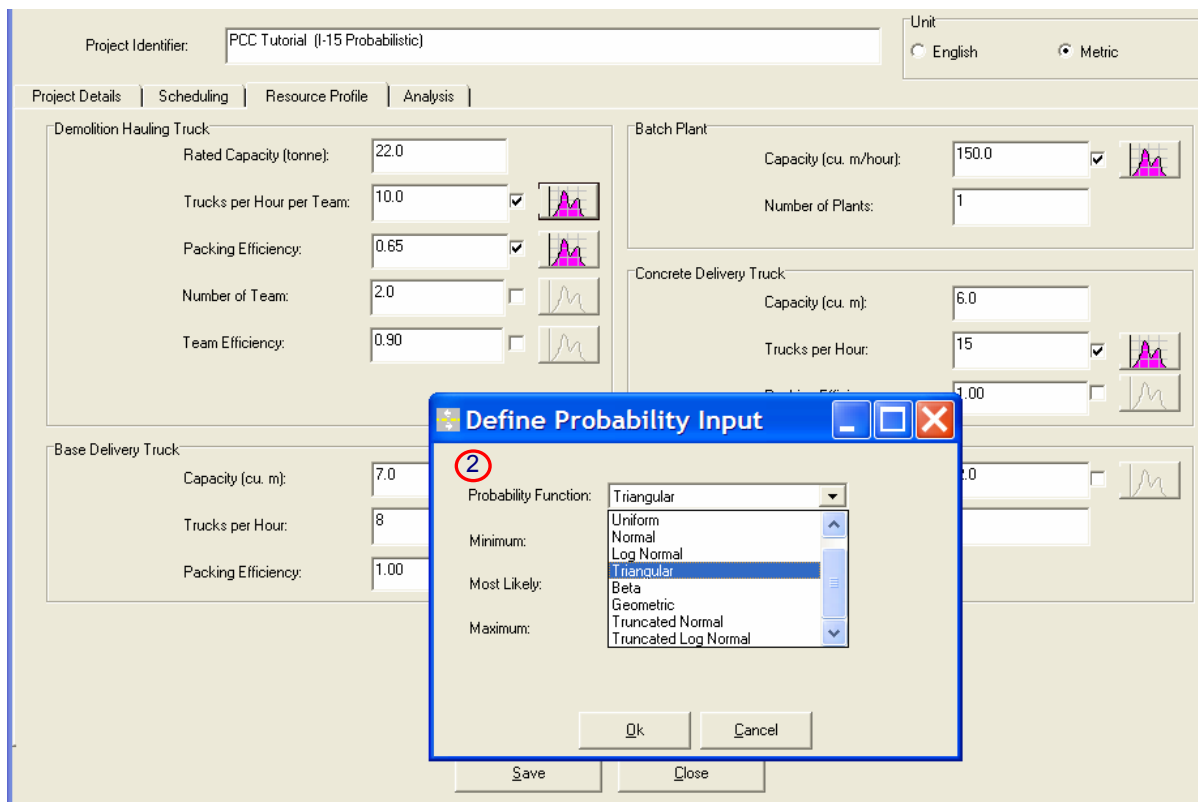


Figure 34: PCC Probabilistic Input – Resource Profile

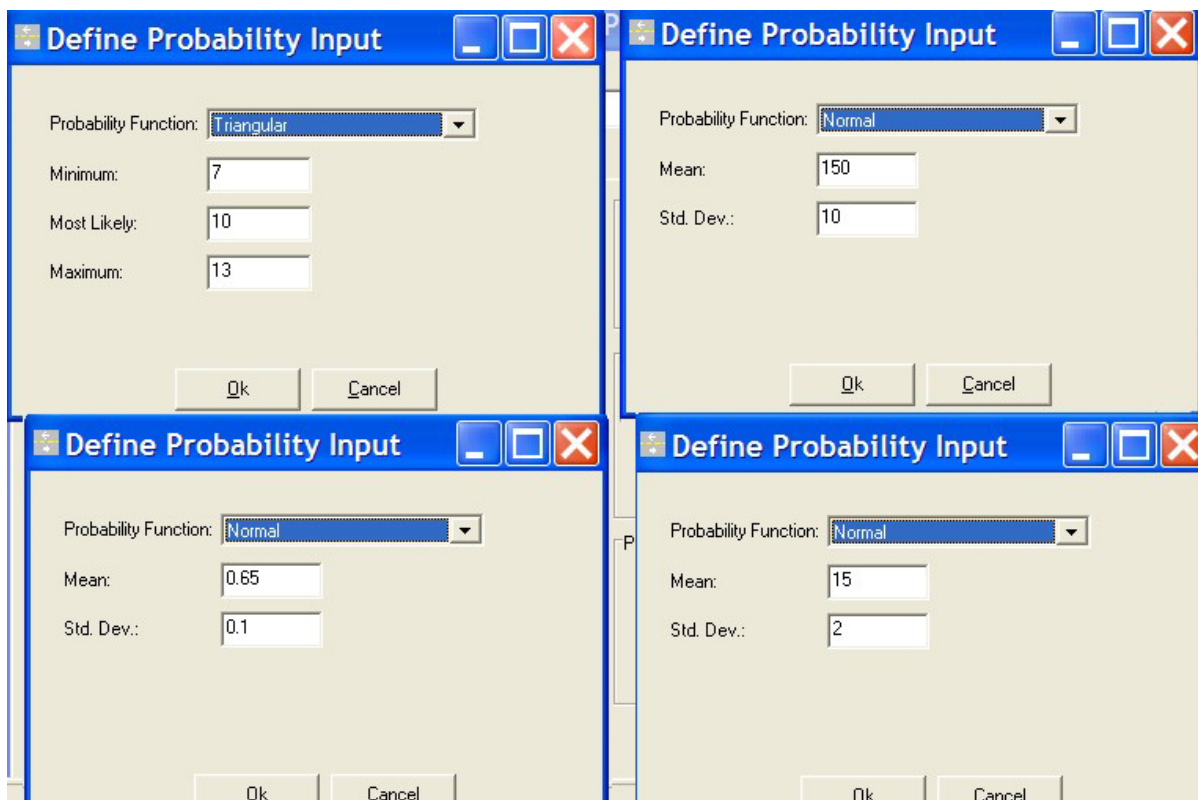


Figure 35: PCC Probabilistic Input – Resource Examples

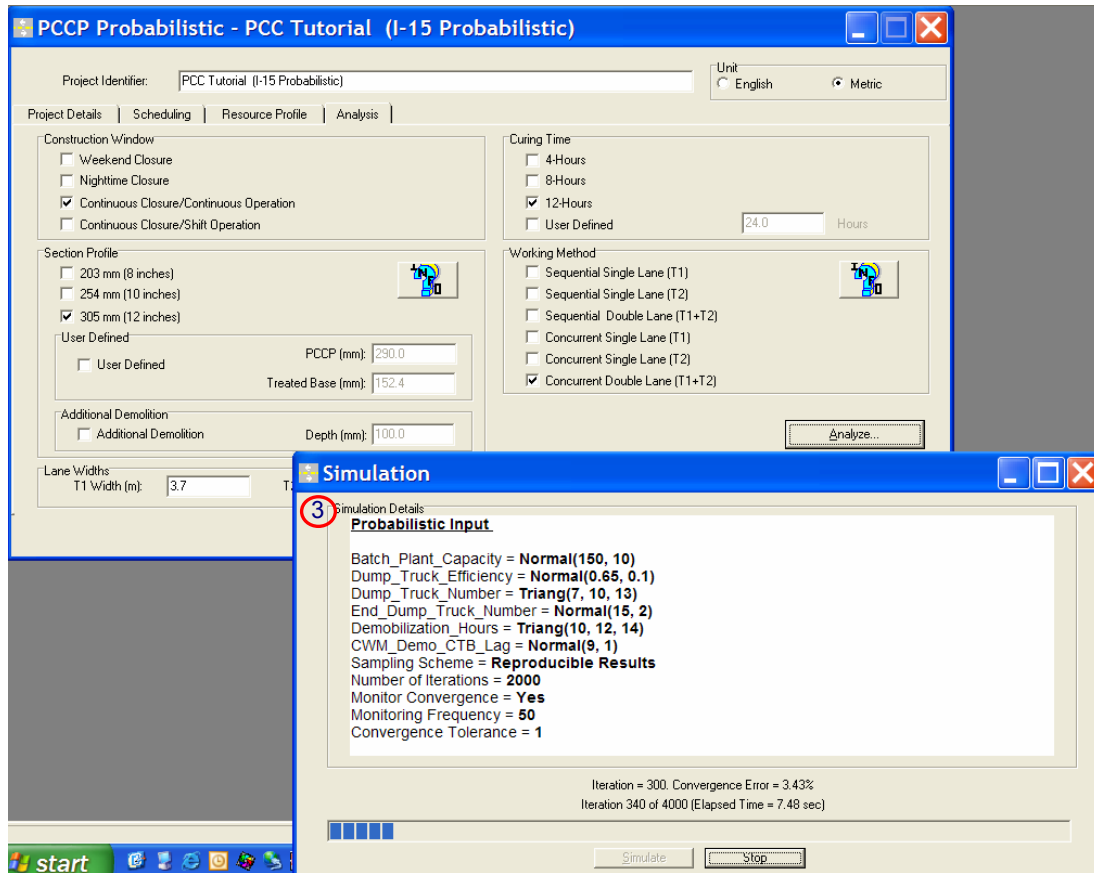


Figure 36: PCC Probabilistic Input – Analysis Window

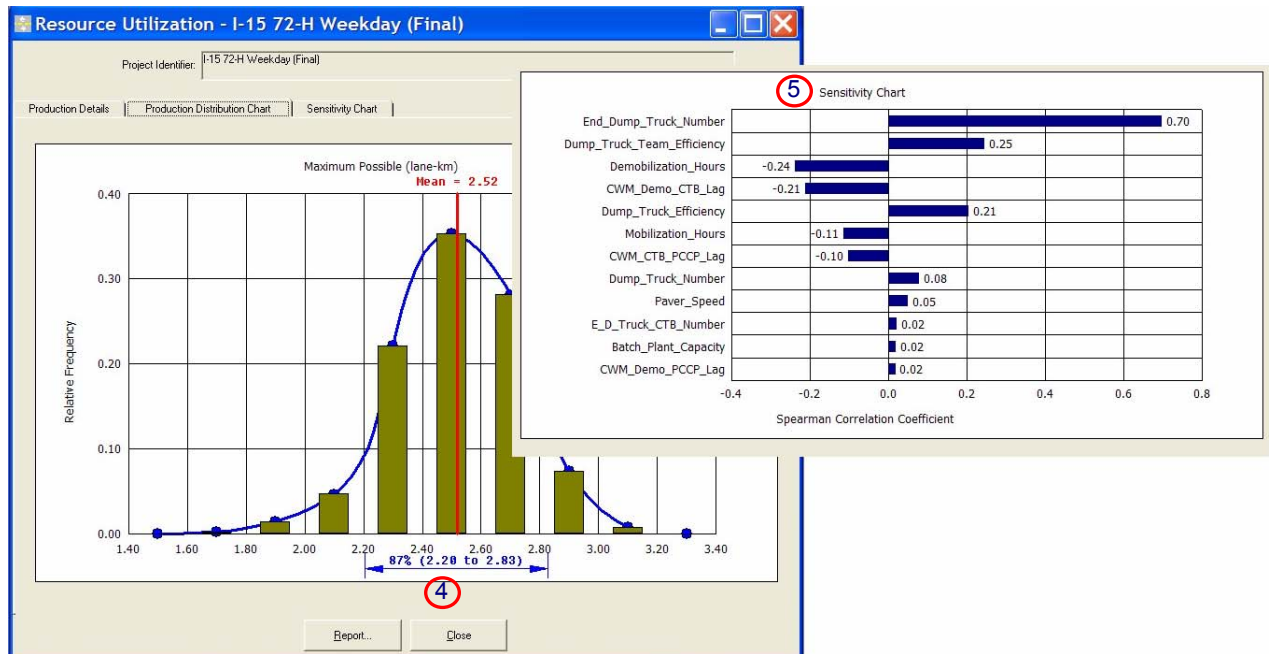


Figure 37: PCC Probabilistic Output -Distribution and Sensitivity Charts

CSOL Depth Deterministic - CSOL Tutorial for I-710 Long Beach (Your...)

Project Identifier: Unit: ☐ English ☒ Metric

Project Details | Scheduling | Resource Profile | Analysis

Project Description:

Analyst Name: Analysis Date:

Route Name:

Begin KM: End KM:

Objective (lane-km):

Location:

Project Notes:

Figure 38: CSOL Determistic Input - Project Details Window

Project Identifier: Unit: ☐ English ☒ Metric

Project Details | Scheduling | Resource Profile | Analysis

Mobilization: Construction Start Date:
Demobilization (Hours):

Half Closure Traffic Switch:

Construction Window Settings

Weekend Closure		Nighttime Closure	
Start Time on Friday:	<input type="text" value="10:00 PM"/>	Start Time on First Day:	<input type="text" value="08:00 PM"/>
End Time on Monday:	<input type="text" value="05:00 AM"/>	End Time on Next Day:	<input type="text" value="06:00 AM"/>
Available Hours:	<input type="text" value="55.0"/>	Available Hours per Day:	<input type="text" value="10.0"/>
Continuous Closure/Continuous Operation		Continuous Closure/Shift Operation	
Start Time on First Day:	<input type="text" value="12:00 AM"/>	Daily Start Time:	<input type="text" value="06:00 AM"/>
No. of Continuous Work Days:	<input type="text" value="7.0"/>	No. of Continuous Work Days:	<input type="text" value="6.0"/>
Available Hours per Day:	<input type="text" value="24.0"/>	Available Hours per Day:	<input type="text" value="16.0"/>

Figure 39: CSOL Determistic Input - Scheduling Window

Project Identifier: CSOL Tutorial for I-710 Long Beach (Your Name) Unit: ☐ English ☒ Metric

Project Details | Scheduling | Resource Profile | Analysis

Batch Plant (1)

Capacity (tonne/hour): 400.0

Number of Plants: 1

Paver (3)

Non Paving Travel Speed (kph): 30.0

HMA Delivery Truck (2)

Rated Capacity (tonne): 24.0

Trucks per Hour: 15

Packing Efficiency: 1.00

Figure 40: CSOL Deterministic Input - Resource Profile Window

5.5.2. CSOL Analysis Inputs Window

A screenshot of the CSOL **Analysis** Inputs Window is provided in Figure in Figure 41. Refer to the corresponding circled numbers below and in the figure for information on the input variable.

- ① **Section Profile:** Unlike the PCCP module, the user is required to build up the CSOL Section Profile by clicking the **Define** button and checking either one or both Profile A and B. The ACP Layer Definition sub-window pops up for the user to continue further input entries for Lift Thickness, Lift Name, and Cooling Time. Although it can be overwritten, paving speed in the last column is automatically generated in the algorithm base on an empirical formula developed in consultation with the paving industry.
- ② **Shoulder Overlay:** A common practice in CSOL is to overlay the median and outside shoulder together with the overlay of the main lanes within the closure, which is the default option of Simultaneous Paving in the input. Some exceptional projects might have Pre-paving Shoulder Overlay, where shoulder overlay is excluded from the main closure and performed separately before or after the main lane overlay with barriers provided between the shoulders and main lanes.
- ③ **Working Method:** Two types of lane closure (Full- versus Half-Closure) are provided in the CSOL module with the sub-option of two alternatives (Full- versus Partial-Completion) in terms of the completion of paving the cross section.

- ④ **Cooling Time Analysis:** In the AC paving operation, especially with multiple layers in the hot weather, the AC cooling time should be checked to have any interference (paving suspension). The user specified option allows the user to directly input Lift Cooling Time (hour) in the third column of the ACP Layer Definition sub-window. Alternatively, if the user does not have cooling time information or would like to have a more realistic analysis, the user can choose the *MultiCool* Computed option. When the **MultiCool Data** button is clicked, a sub-window pops up so the user may further input entries such as Existing Surface, Mix Specifications, and Environmental Condition (Figure 42). The main *CA4PRS* program calls the Multi Color subroutine to calculate AC cooling time and check any paving suspension through numerous iterations.
- ⑤ **Lane Width:** When the **Lane Width** button is clicked, the number of lanes for CSOL is defined with lane width in a sub-window.

The screenshot displays the 'Analysis' tab of the CA4PRS software. The main window contains several sections: 'Construction Window' with checkboxes for 'Weekend Closure', 'Nighttime Closure', 'Continuous Closure/Continuous Operation', and 'Continuous Closure/Shift Operation'; 'Section Profile' with 'Define...' buttons and checkboxes for 'Profile A' and 'Profile B'; 'Shoulder Overlay' with radio buttons for 'Pre-paving' and 'Simultaneous Paving', and input fields for 'Shoulder Width (m)' (Inside: 3.05, Outside: 2.13); 'Working Method' with checkboxes for 'Full Closure', 'Half Closure/Full Completion', and 'Half Closure/Partial Completion', and a 'No of Lifts Before Traffic Switch' input field (2); 'Cooling Time Analysis' with radio buttons for 'User Specified' and 'MultiCool Computed', and a 'MultiCool Data...' button; and 'Lane Widths' with a 'No of Lanes' input field (3) and a 'Lane Width...' button. An 'Analyze...' button is located at the bottom right.

Two sub-windows are overlaid on the main window:

- ① ACP Layer Definition - Profile A:** This window contains a table with 5 columns: Lift Number, Lift Thickness (mm), Lift Name, Lift Cooling Time (hour), and Paver Speed (kph). The table has 3 rows of data and a summary row. Below the table are buttons for 'Insert', 'Delete', 'Ok', and 'Cancel'.
- ⑤ Lane Widths:** This window contains a table with 2 columns: Lane Number and Lane Width (m). The table has 3 rows of data. Below the table are buttons for 'Ok' and 'Cancel'.

Lift Number	Lift Thickness (mm)	Lift Name	Lift Cooling Time (hour)	Paver Speed (kph)
3	76.20	PBA-6a	3.00	4.43
2	85.00	AR-8000	1.00	3.90
1	45.00	AR-8000(leveling coat)	1.00	6.30
Total: 206.20		Average: 1.67		Average: 4.88

Lane Number	Lane Width (m)
1	3.66
2	3.66
3	3.66

Figure 41: CSOL Deterministic Input – Analysis Windows

4 MultiCool Data

Construction Start Date: 7/17/2003

Latitude (Deg North): 40.0

Existing Surface

Material Type: PCCP

Moisture Content: Dry

Moisture State: Unfrozen

Surface Temperature (C): 21.1

Mix Specifications

Mix Type: Dense Graded

Delivery Temperature (C): 148.89

Stop Temperature (C): 73.89

Open to Traffic Temperature (C): 61

Environmental Condition				
Period	Time	Ambient Temperature (C)	Average Wind Speed (kph)	Sky Conditions
1	12:00 AM	12.8	8.1	Clear & Dry
2	06:00 AM	15.6	8.1	Clear & Dry
3	12:00 PM	26.7	8.1	Clear & Dry
4	06:00 PM	18.3	8.1	Clear & Dry

Figure 42: CSOL Analysis Input - Multi-Cool Window

5.6. FDAC ANALYSIS INPUTS AND OUTPUTS

The basic layout of the FDAC module is similar to the PCCP and CSOL modules: see Figure 43 for **Project Details**, Figure 44 for **Scheduling**, Figure 45 for **Resource Profile**, and Figure 46 for **Analysis** input tab windows respectively.

Additional details for inputs in the FDAC **Resource Profile** window (Figure 45) are:

- ① **Dump Truck:** similar to demolition hauling trucks in the PCCP module
- ② **Paper:** similar to non-paving paver travel speed defined in the CSOL module
- ③ **Batch Plant:** similar to the batch plant defined in the CSOL module
- ④ **Semi-bottom Truck:** similar to HMA delivery trucks defined in the CSOL module

The basic FDAC analyses outputs (Figure 49) are similar to CSOL outputs (Figure 48), and the interpretation of the CSOL and FDAC outputs are similar to the PCC analysis outputs.

5.7. DATABASE MANAGEMENT

Data for the *CA4PRS* analysis are stored in a M.S. Access database file (filename **LLPRS.MDB**) in the folder where the software is installed (usually **C:\Program Files\CA4PRS** as default). The user can backup (export) this database file or open (import) other database file in the main menu: **File => Open Database (or Backup)**. The user should designate the name and location of the database file to copy or open when the Database File Name sub-window pops up (Figure 50). This menu is useful for *CA4PRS* database management especially when the user wants to copy its own analysis data from one computer to another.

The screenshot shows a software window titled "Full Depth Deterministic - FDAC Tutorial for I-710 Long Beach ...". The window has a blue title bar and standard Windows window controls. Inside, there's a "Project Identifier:" field with the text "FDAC Tutorial for I-710 Long Beach (Your Name)". To the right is a "Unit" section with radio buttons for "English" and "Metric", where "Metric" is selected. Below this is a tabbed interface with four tabs: "Project Details", "Scheduling", "Resource Profile", and "Analysis". The "Project Details" tab is active. It contains several input fields: "Project Description:" with the text "Caltrans AC (Full Depth) Demonstration Project"; "Analyst Name:" with "Your Name" and "Analysis Date:" with a dropdown showing "3 / 1 / 2006"; "Route Name:" with "I-710 Long Beach"; "Begin KM:" with "5.00" and "End KM:" with "10.00"; "Objective (lane-km)" with "4.50"; "Location:" with "Long Beach, CA"; and "Project Notes:" with the text "3 lanes each direction" and "Underneath overbridges (PCH, Willow, I-405)".

Figure 43: FDAC Deterministic Input – Project Details Window

Project Identifier: Unit: ☐ English ☒ Metric

Project Details | **Scheduling** | Resource Profile | Analysis

Mobilization
 Mobilization (Hours):
 Demobilization (Hours):

Construction Start Date:

Lag Time between Demolition and Paving
 Paving can begin before Demolition is Complete: ☐
 Demolition to Paving (Hours):

Construction Window...

Construction Window Settings

Weekend Closure
 Start Time on Friday:
 End Time on Monday:
 Available Hours:

Nighttime Closure
 Start Time on First Day:
 End Time on Next Day:
 Available Hours per Day:

Continuous Closure/Continuous Operation
 Start Time on First Day:
 No. of Continuous Work Days:
 Available Hours per Day:

Continuous Closure/Shift Operation
 Daily Start Time:
 No. of Continuous Work Days:
 Available Hours per Day:

Figure 44: FDAC Deterministic Input – Scheduling Windows

Project Identifier: Unit: ☐ English ☒ Metric

Project Details | **Scheduling** | Resource Profile | Analysis

Demolition Hauling Truck
 ① Rated Capacity (tonne):
 Trucks per Hour per Team:
 Packing Efficiency:
 Number of Team:
 Team Efficiency:

Batch Plant
 ③ Capacity (tonne/hour):
 Number of Plants:

HMA Delivery Truck
 ④ Rated Capacity (tonne):
 Trucks per Hour:
 Packing Efficiency:

Paver
 ② Non Paving Travel Speed (kph):

Figure 45: FDAC Deterministic Input – Resource Profile Window

Project Identifier:

Unit: ☐ English ☒ Metric

Project Details | Scheduling | Resource Profile | Analysis

Construction Window

☒ Weekend Closure

☐ Nighttime Closure

☐ Continuous Closure/Continuous Operation

☐ Continuous Closure/Shift Operation

Working Method

☒ Single Lane Paving (T1)

☐ Single Lane Paving (T2)

☐ Double Lane Paving (T1+T2)

Section Profile

Define... ☒ Profile A

Define... ☐ Profile B

Cooling Time Analysis

☒ User Specified

☐ MultiCool Computed

MultiCool Data...

Additional Demolition

☒ Additional Demolition Depth (mm):

Lane Widths

T1 Width (m):

T2 Width (m):

ACP Layer Definition - Profile A

Lift Number	Lift Thickness (mm)	Lift Name	Lift Cooling Time (hour)	Paver Speed (kph)
4	76.20	PBA-6a	3.00	4.43
3	76.20	AR-8000	3.00	4.51
2	76.20	AR-8000	2.00	4.51
1	94.00	Rich Bottom	1.00	3.36
Total: 322.60			Average: 2.25	Average: 4.20

Insert Delete Ok Cancel

Figure 46: FDAC Deterministic Input – Analysis Window

MultiCool Data

Construction Start Date:

Latitude (Deg North):

Existing Surface

Material Type:

Moisture Content:

Moisture State:

Surface Temperature (C):

Mix Specifications

Mix Type:

Delivery Temperature (C):

Stop Temperature (C):

Open to Traffic Temperature (C):

Environmental Condition

Period	Time	Ambient Temperature (C)	Average Wind Speed (kph)	Sky Conditions
1	12:00 AM	12.8	8.1	Clear & Dry
2	06:00 AM	15.6	8.1	Clear & Dry
3	12:00 PM	26.7	8.1	Clear & Dry
4	06:00 PM	18.3	8.1	Clear & Dry

Figure 47: FDAC Deterministic Input - Multicool Data

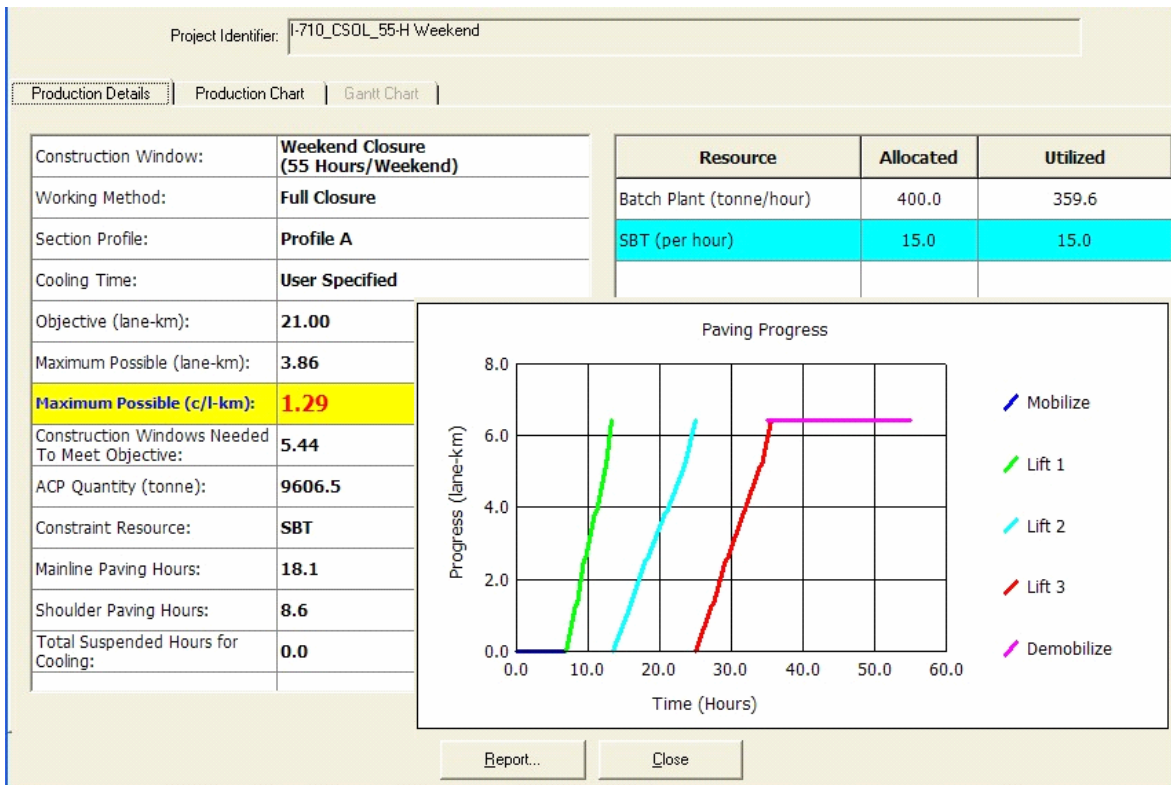


Figure 48: CSOL Deterministic Output - Production Details and Chart

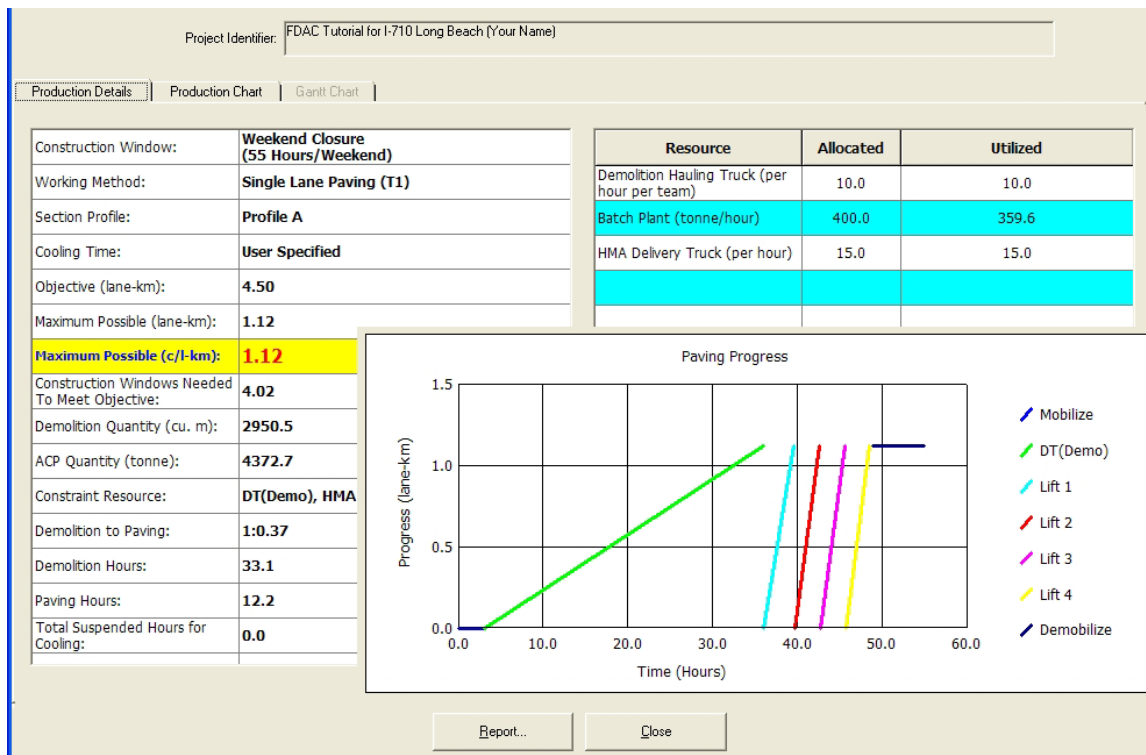


Figure 49: FDAC Deterministic Output - Production Details and Chart

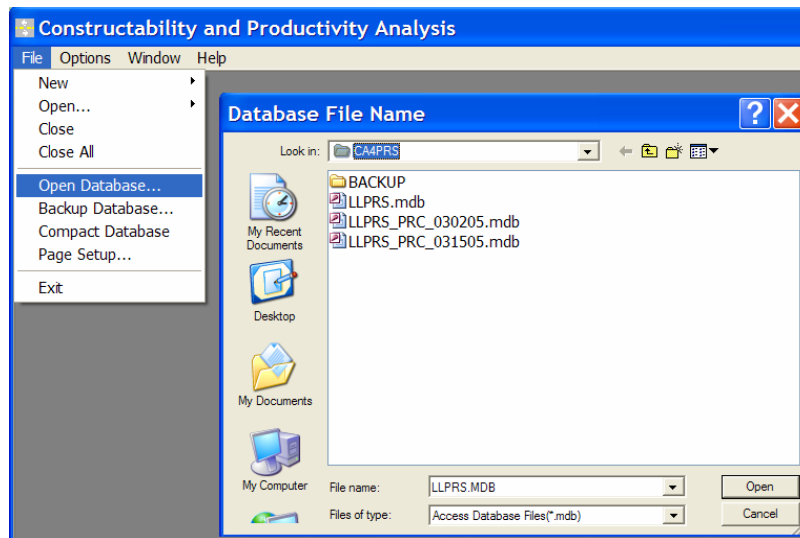


Figure 50: Database Management - Open Other Database File

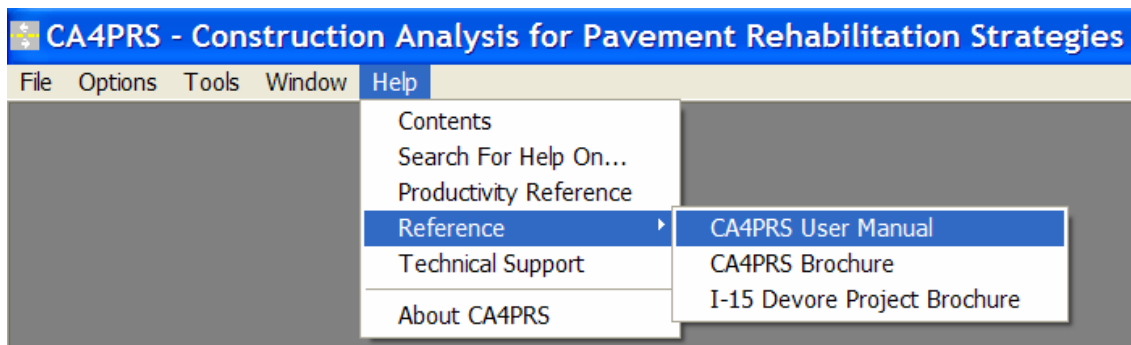


Figure 51: References in the Help Main Menu

Table 2: Reference Data for Production Rates from Previous LLPRS Projects.

Project Name	Major Activities	Estimated Quantity	Duration (Hours)	Avg. Hourly Trucks Per Crew	Avg. Loading or Unloading Cycle Time (min.)	Avg. Production Rate
I-10 Pomona	Non-impact Slab Demolition	2,080 m ³	30.0	9.0	5.5	68.3 m ³ /hour
	FSHCC Screed Paving	2,089 m ³	47.0	10.0	4.0	44.3 m ³ /hour
I-710 Long Beach	Impact Slab Demolition	4,065 m ³	22.5	12.1	5.0	183.3 m ³ /hour
	Roadway Bucket-out Excavation	7,416 m ³	35.5	9.9	3.0	195.9 m ³ /hour
	Aggregate Base Placement	2,159 m ³	18.0	7.4	1.0	113.8 m ³ /hour
	CSOL AC Overlay	19,570 tonne	54.7	16.0	4.0	357.0 tonne/hour
	FDAC AC Paving	14,289 tonne	55.0	11.6	5.0	247.9 tonne/hour
I-15 Devore	Non-impact Slab Demolition	8,121 m ³	104.7	8.3	7.0	76.7 m ³ /hour
	Road Base Milling	7,473 m ³	61.8	13.1	2.0	133.7 m ³ /hour
	AC Base Paving	5,128 m ³	54.6	12.3	2.0	92.1 m ³ /hour
	RSC Slip-form Paving	9,941 m ³	90.4	17.3	1.0	109.9 m ³ /hour



Figure 52: CA4PRS Reference Information on Caltrans DRI Website
at: <http://www.dot.ca.gov/research/roadway/ca4prs/index.htm>

or Intranet OnRamp at:

http://onramp.dot.ca.gov/newtech/offices/materials_and_infrastructure/rmi_branch/

The CA4PRS Software is downloadable free from the above intranet (OnRamp) site or with the following login information from the above internet site.

User Name: caltrans-ca4prs

Password: sptc-ca4prs

6. TRAFFIC IMPACT ANALYSIS MODULE

6.1. ROAD USER COST ANALYSIS

The UCB ITS has developed a user-friendly, computer-based (Microsoft Excel) version of a traffic Demand-Capacity analysis model based on Highway Capacity Manual (HCM) to calculate the road user cost (RUC) during the rehabilitation. The basic delay calculation compares traffic demand and capacity of the roadway (Figure 53). Where the demand exceeds capacity, the total road user delay measured in vehicle-hours can be estimated with geometric relationships comparing the two (demand and capacity) curves (Figure 54). The detailed delay formulas can be found in Chapter 29 of the HCM 2000. RUC is obtained by simply multiplying the total delay in vehicle-hours by a dollar value of time. \$9/hour for passenger cars and \$24/hour for commercial trucks were used as the time values of RUC according to Caltrans guidelines, which are similar to standards in other states.

The RUC spreadsheet is called in from the CA4PRS main menu: Tools => Open Road User Cost Workbook (Figure 55). As the delay calculation process in the RUC spreadsheet uses many macro links, the user should adjust the macro security level to “LOW” in the Excel main menu: Tools => Macro => Security (Figure 56). RUC input variables include: before construction lane configurations and speed limit for normal freeway operations; construction work zone parameters (i.e. speed limit, length, number of closures, length of closure, construction date); traffic demand input and traffic growth rate; vehicle cost for passenger vehicles and trucks; and capacity information before and during construction (see Figure 57). The RUC has built-in formula help the user calculate adjusted CWZ capacity as a function of basic capacity, truck percentage, and geographic terrain based on HCM, as shown in Figure 58. Figure 59 shows two screen shots of supplemental screens that allow for the input of hourly traffic demand data by direction of travel, along with lane closure schedule by hour of day and by direction of travel during the construction period in Figure 60. Another screen shot of the Demand-Capacity Model output is shown in Figure 61. The outputs include average queue length, maximum delay per vehicle per closure, and total user delay cost per direction as the comparison of delay conditions before construction and during construction. It is important to note that the Demand-Capacity analysis does not take into account the impacts of traffic diversion on alternative routes, which is considered in traffic network (macro, micro, or mesoscopic) simulations. RUC outputs also show the sensitivity of traffic demand reduction (Figure 62) and CWZ roadway capacity (Figure 63).

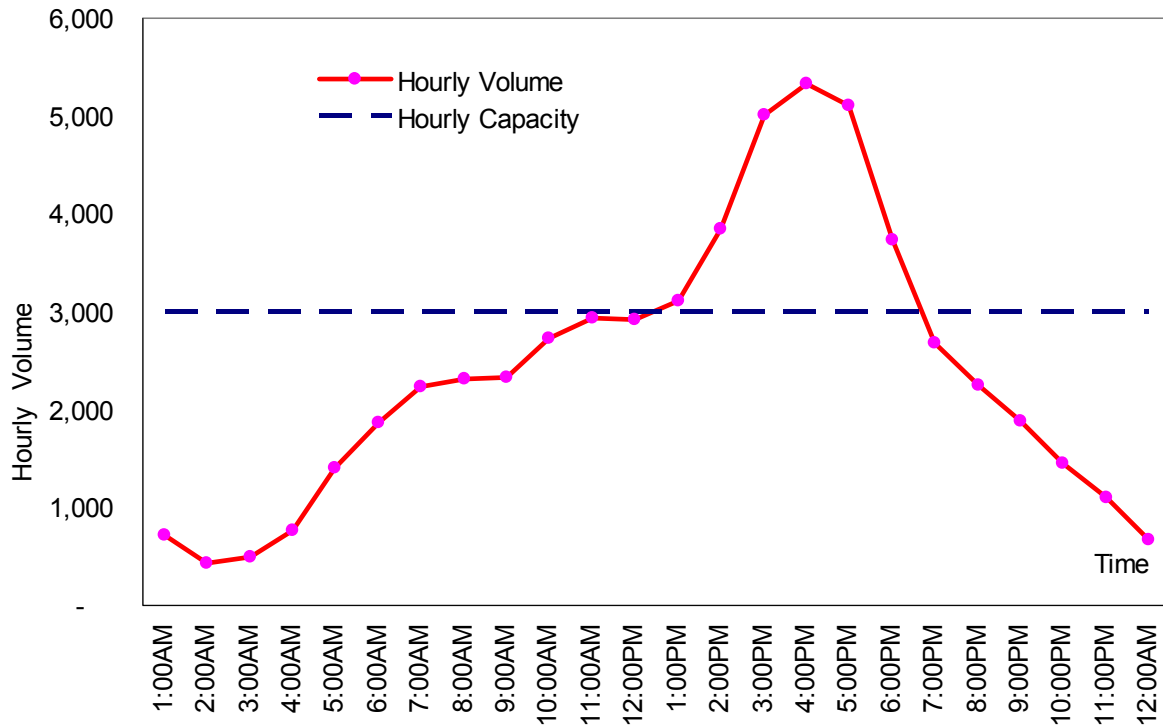


Figure 53: Hourly Traffic Demand versus Roadway Capacity Graph

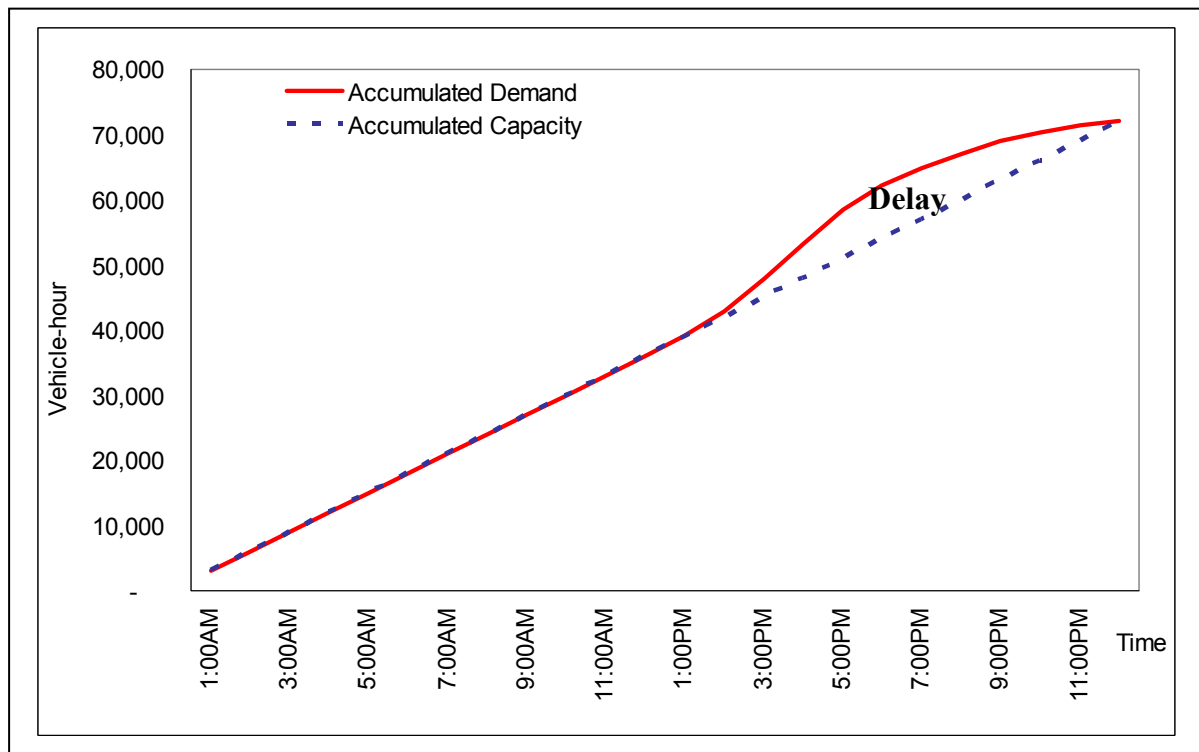


Figure 54: Delay in Vehicle-hour When Comparing Demand with Capacity

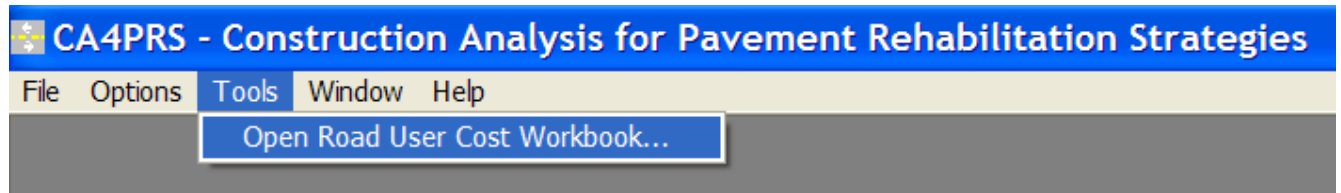


Figure 55: Open RUC Spreadsheet in the Tools Menu

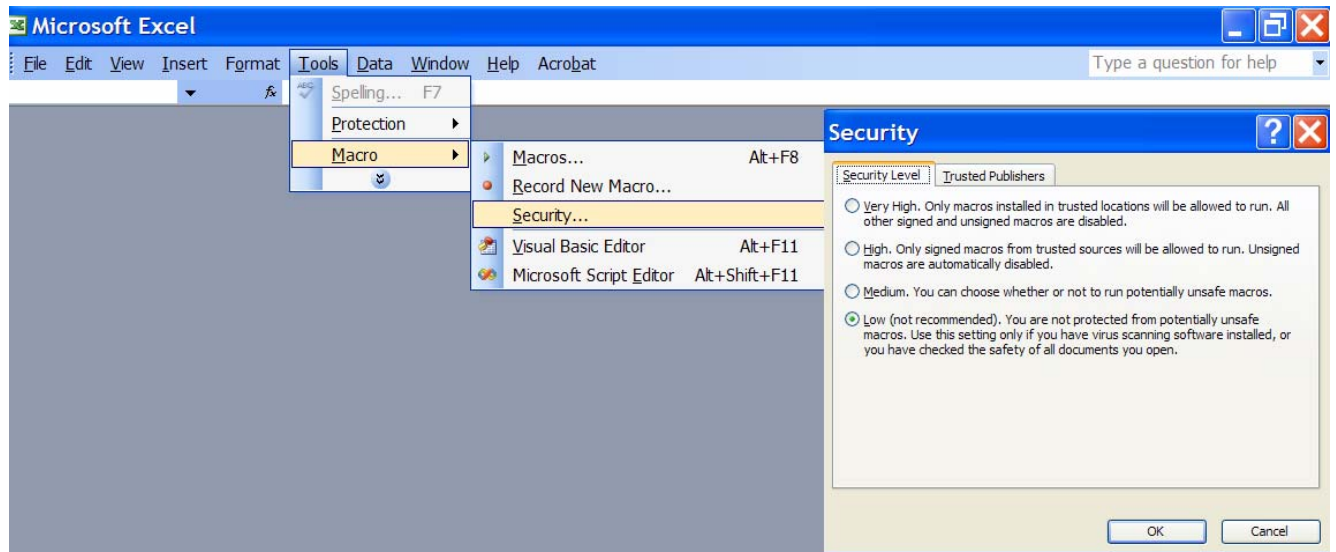
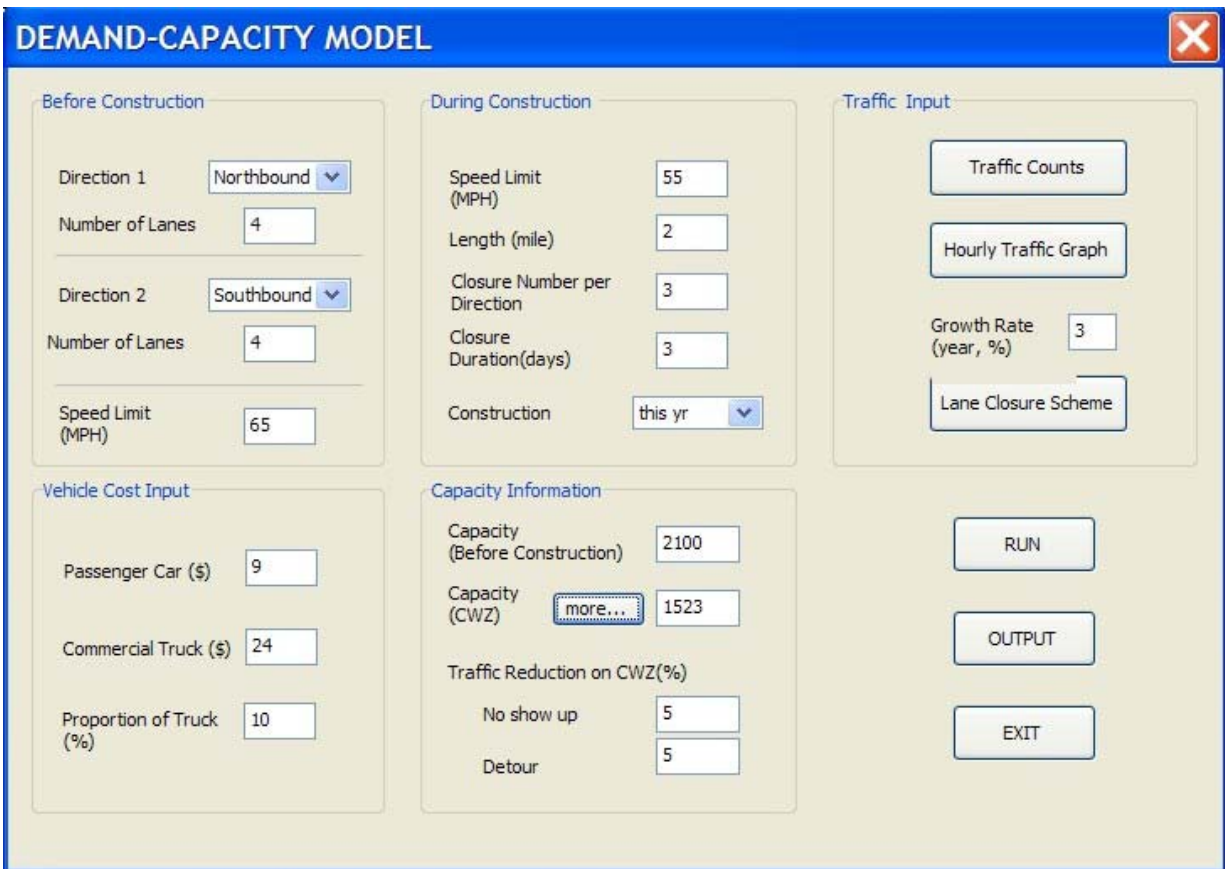


Figure 56: Adjust Security Level to Low in MS Excel



DEMAND-CAPACITY MODEL

Before Construction

Direction 1: Northbound (dropdown)
 Number of Lanes: 4
 Direction 2: Southbound (dropdown)
 Number of Lanes: 4
 Speed Limit (MPH): 65

During Construction

Speed Limit (MPH): 55
 Length (mile): 2
 Closure Number per Direction: 3
 Closure Duration(days): 3
 Construction: this yr (dropdown)

Traffic Input

Traffic Counts
 Hourly Traffic Graph
 Growth Rate (year, %): 3
 Lane Closure Scheme

Vehicle Cost Input

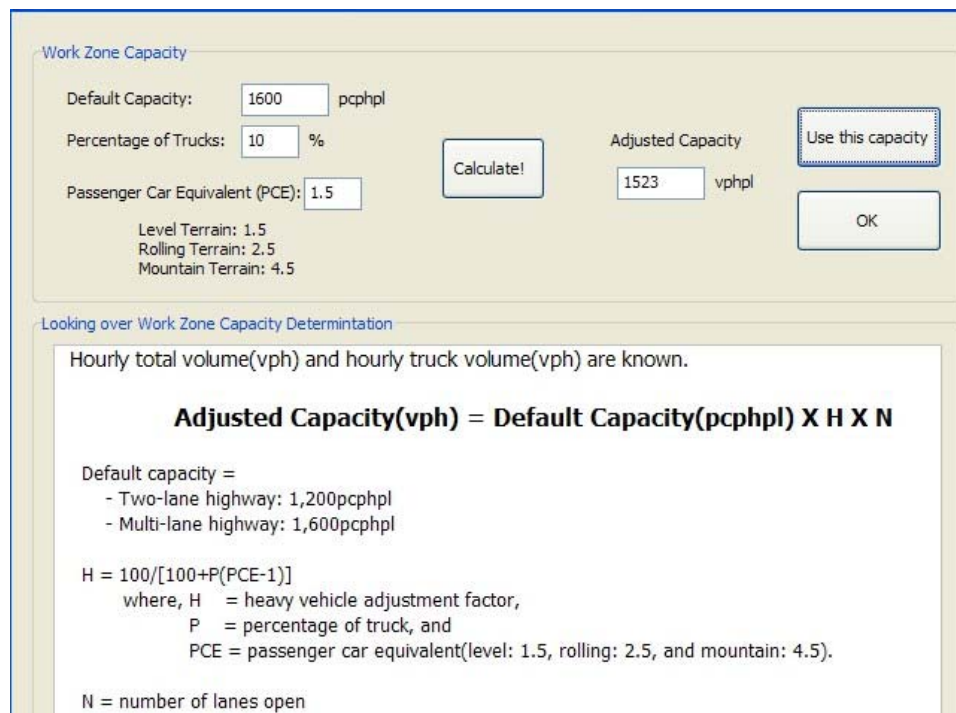
Passenger Car (\$): 9
 Commercial Truck (\$): 24
 Proportion of Truck (%): 10

Capacity Information

Capacity (Before Construction): 2100
 Capacity (CWZ): more... 1523
 Traffic Reduction on CWZ(%)
 No show up: 5
 Detour: 5

Buttons: RUN, OUTPUT, EXIT

Figure 57: Road User Cost – Main Input Window



Work Zone Capacity

Default Capacity: 1600 pcphpl
 Percentage of Trucks: 10 %
 Passenger Car Equivalent (PCE): 1.5
 Level Terrain: 1.5
 Rolling Terrain: 2.5
 Mountain Terrain: 4.5

Buttons: Calculate!, Use this capacity, OK

Adjusted Capacity
 1523 vphpl

Looking over Work Zone Capacity Determination

Hourly total volume(vph) and hourly truck volume(vph) are known.

Adjusted Capacity(vph) = Default Capacity(pcphpl) X H X N

Default capacity =
 - Two-lane highway: 1,200pcphpl
 - Multi-lane highway: 1,600pcphpl

$H = 100/[100+P(PCE-1)]$
 where, H = heavy vehicle adjustment factor,
 P = percentage of truck, and
 PCE = passenger car equivalent(level: 1.5, rolling: 2.5, and mountain: 4.5).

N = number of lanes open

Figure 58: Road User Cost – CWZ Capacity Determination

Demand Input Window

You may type or load demands from the sheet.

Hourly Demand

	Direction 1		Direction 2			Direction 1		Direction 2	
	Northbound	Southbound				Northbound	Southbound		
12:00-01:00AM	651	556			12:00-01:00P	2843	2932		
01:00-02:00AM	389	608			01:00-02:00PM	3521	2937		
02:00-03:00AM	454	935			02:00-03:00PM	4585	3041		
03:00-04:00AM	699	2251			03:00-04:00P	4872	3138		
04:00-05:00AM	1279	3740			04:00-05:00P	4680	2903		
05:00-06:00AM	1702	4419			05:00-06:00PM	3418	2086		
06:00-07:00AM	2039	4281			06:00-07:00P	2459	1454		
07:00-08:00AM	2123	2985			07:00-08:00P	2059	1352		
08:00-09:00AM	2134	2596			08:00-09:00P	1717	1173		
09:00-10:00AM	2501	2536			09:00-10:00P	1334	1027		
10:00-11:00AM	2681	2498			10:00-11:00P	1003	682		
11:00-12:00PM	2676	2522			11:00-12:00A	620	651		
	SUM					52439	53303		

Clean demands

Load demands

If hourly counts are not available:

CA historical data

OK

Cancel

Figure 59: Road User Cost-Hourly Traffic Counts Input Window

Construction Input

Lane Closure Period

Select number of lanes for both directions during construction: 4

Select number of lanes per direction by time.

	Direction 1		Direction 2			Direction 1		Direction 2	
12:00-01:00AM	2	2			12:00-01:00PM	2	2		
01:00-02:00AM	2	2			01:00-02:00PM	2	2		
02:00-03:00AM	2	2			02:00-03:00PM	2	2		
03:00-04:00AM	2	2			03:00-04:00PM	2	2		
04:00-05:00AM	2	2			04:00-05:00PM	2	2		
05:00-06:00AM	2	2			05:00-06:00PM	2	2		
06:00-07:00AM	2	2			06:00-07:00PM	2	2		
07:00-08:00AM	2	2			07:00-08:00PM	2	2		
08:00-09:00AM	2	2			08:00-09:00PM	2	2		
09:00-10:00AM	2	2			09:00-10:00PM	2	2		
10:00-11:00AM	2	2			10:00-11:00PM	2	2		
11:00-12:00PM	2	2			11:00-12:00AM	2	2		

OK

Cancel

Figure 60: Road User Cost- Hourly Lane Closure Input Window

RUC Estimation Output

Before Construction		During Construction		Total Difference	
Direction 1		Direction 1		Direction 1	
Average Queue Length	0 Mile	Average Queue Length	6 Mile	Average Queue Length	6 Mile
Max. Delay/Veh/Closure	0 Minute	Max. Delay/Veh/Closure	73 Minute	Max. Delay/Veh/Closure	73 Minute
Total User Delay	\$0.00 US	Total User Delay	\$1,593,791.00 US	Total User Delay	\$1,593,791.00 US
Direction 2		Direction 2		Direction 2	
Average Queue Length	0 Mile	Average Queue Length	3 Mile	Average Queue Length	3 Mile
Max. Delay/Veh/Closure	0 Minute	Max. Delay/Veh/Closure	42 Minute	Max. Delay/Veh/Closure	42 Minute
Total User Delay	\$0.00 US	Total User Delay	\$711,393.00 US	Total User Delay	\$711,393.00 US

Graphical Output
Demand-Capacity Curve
Demand Sensitivity
Capacity Sensitivity

For printing output, please go to "FINAL OUTPUT" sheet.

Close

Figure 61: Road User Cost – Main Output Window

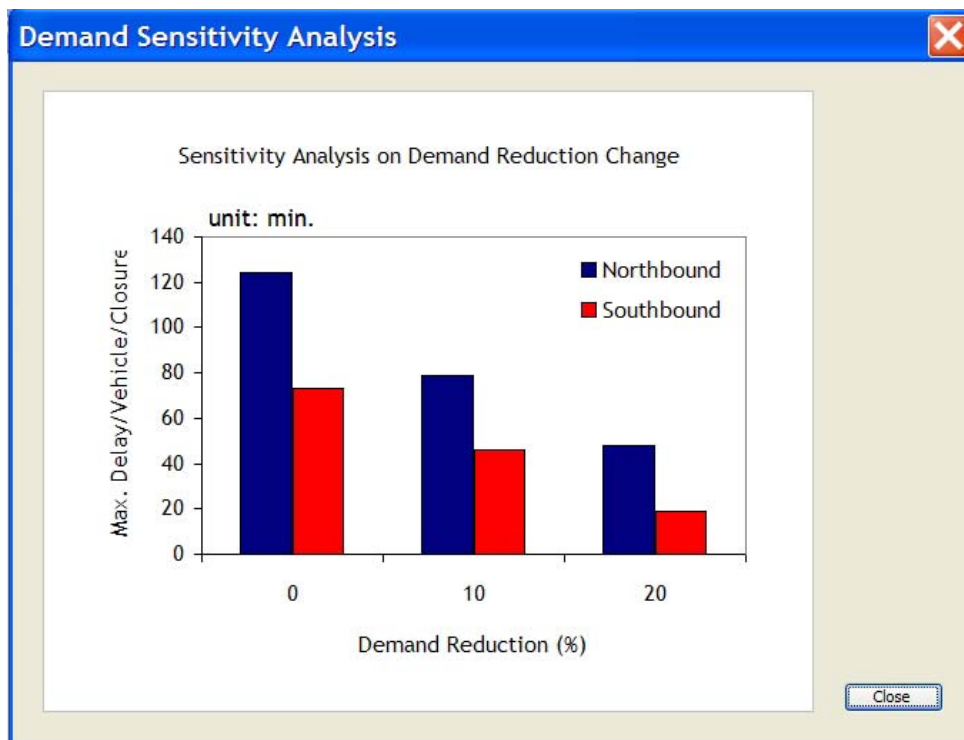


Figure 62: Road User Cost – Demand Sensitivity Graph

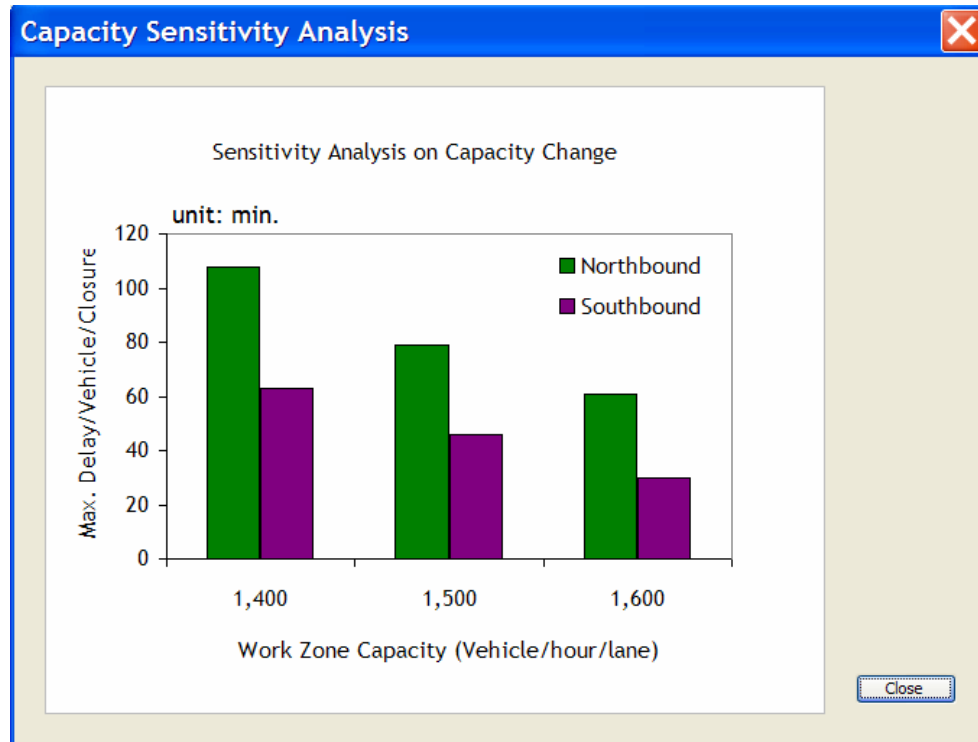


Figure 63: Road User Cost – Capacity Sensitivity Graph

6.2. TRAFFIC DATA MEASUREMENT SYSTEM: PEMS

The ITS in the University of California at Berkeley has developed a way to get updates on traffic hotspots, alternative routes and travel times - up to an hour in advance - via the Internet or cellular phone. The Freeway Performance Measurement System (PeMS) (Figure 64) is a repository for real-time traffic data that streams into the California Department of Transportation from thousands of loop detectors, hexagon-shaped wire sensors in the pavement that count cars and measure average speed. PeMS converts freeway monitoring data into real-time traffic updates accessible via a Web portal (Figure 65). At the heart of PeMS is software that converts data from Caltrans' existing vehicle detection network into easy-to-read tables and graphs. The PeMS Web page provides a map of the entire freeway system in a given urban area (Figure 66). A color-coded link provides the freeway speed, and an animation shows how congestion starts and spreads. PeMS also analyses traffic patterns and predicts travel times up to an hour in advance (Figure 67). While PeMS has obvious advantages for commuters, it was originally designed the system to help Caltrans officials monitor traffic patterns (see Figure 68 Figure 69 as examples).

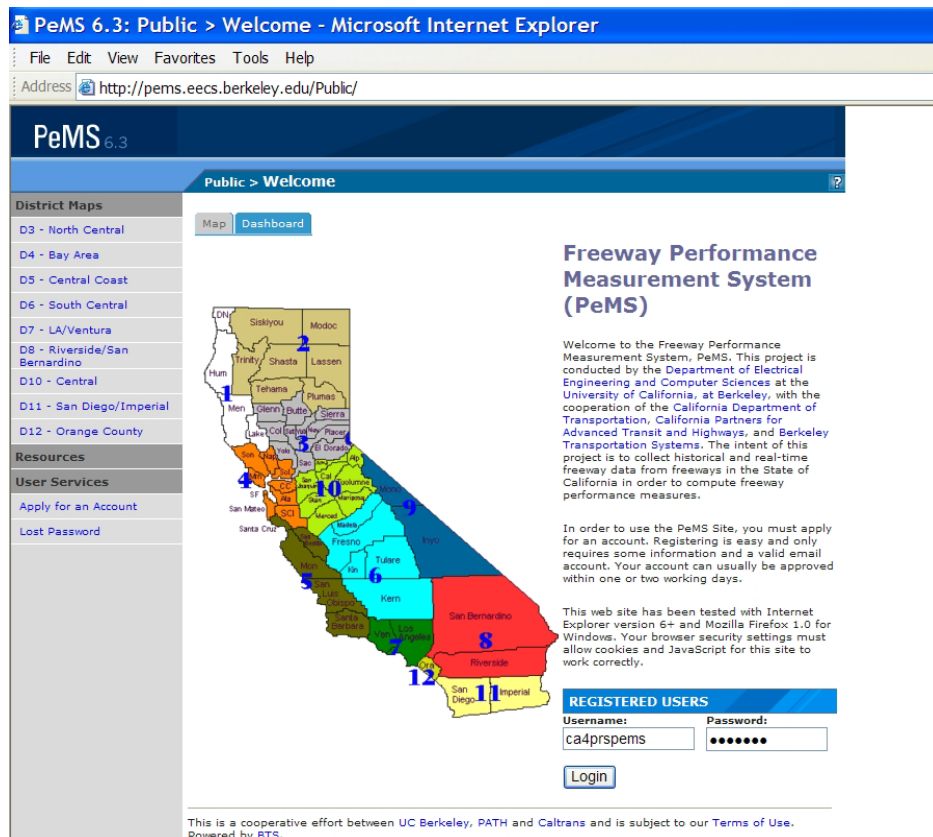


Figure 64: Caltrans/UC Berkeley PeMS Login at:

<http://pems.eecs.berkeley.edu/Public/> with
Username: **ca4prspems** + Password: **horsee9**

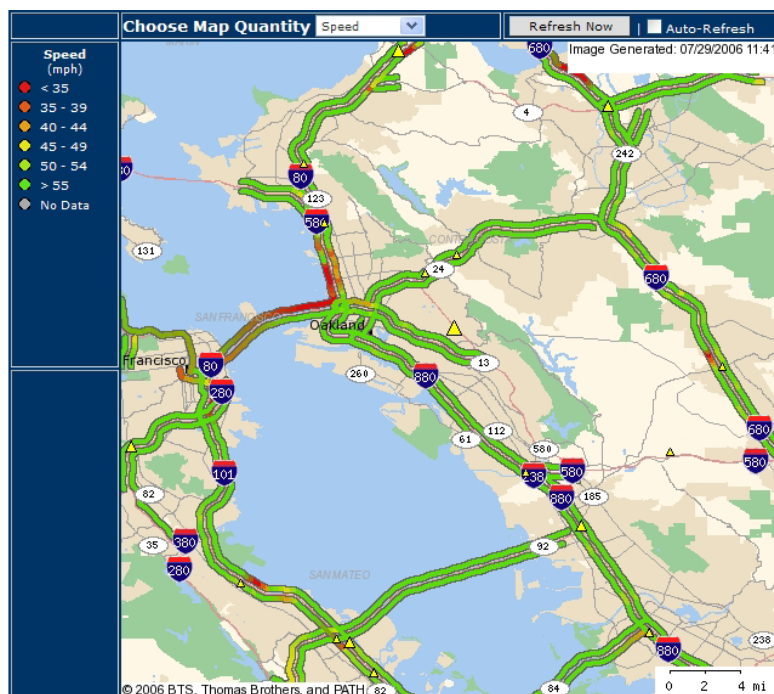


Figure 65: PeMS Real-time Traffic Condition on the Web

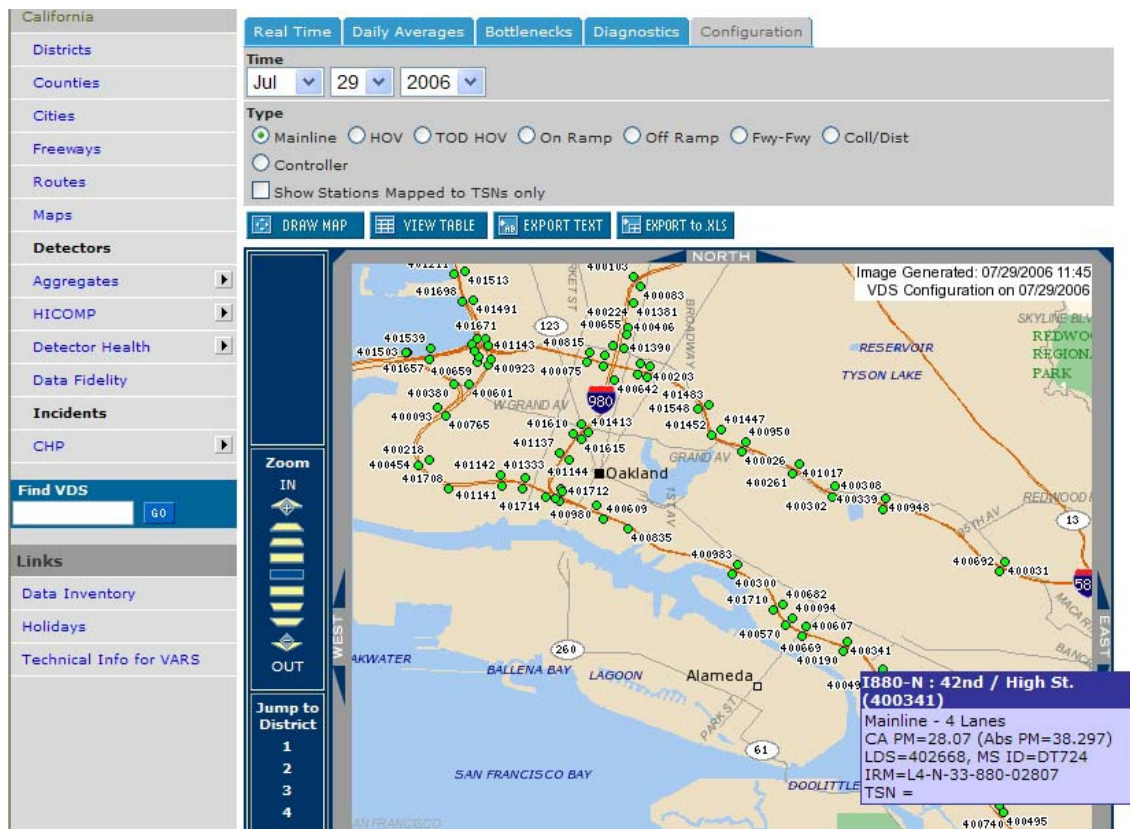


Figure 66: PeMS Configuration for the Loop Detector Station on I-880 High Street

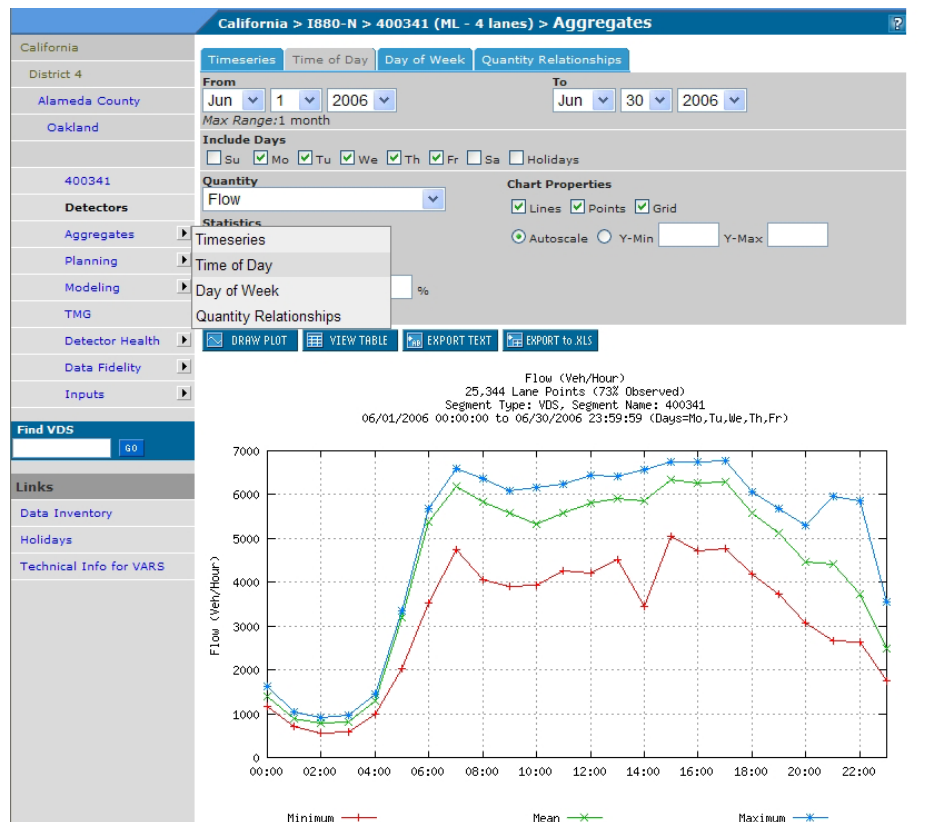


Figure 67: PeMS Historical Database for Hourly/Daily Traffic Flow

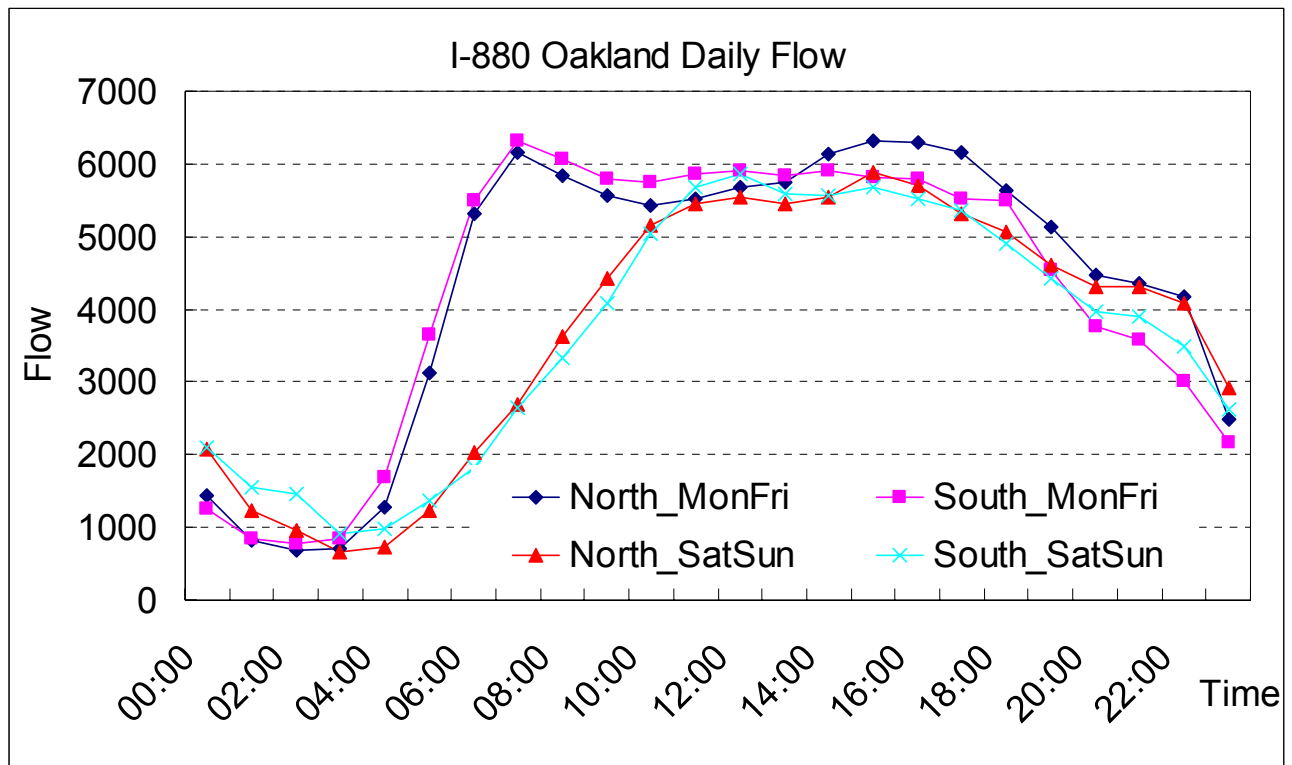


Figure 68: I-880 Oakland (High Street) Daily Traffic Flow (PeMS)

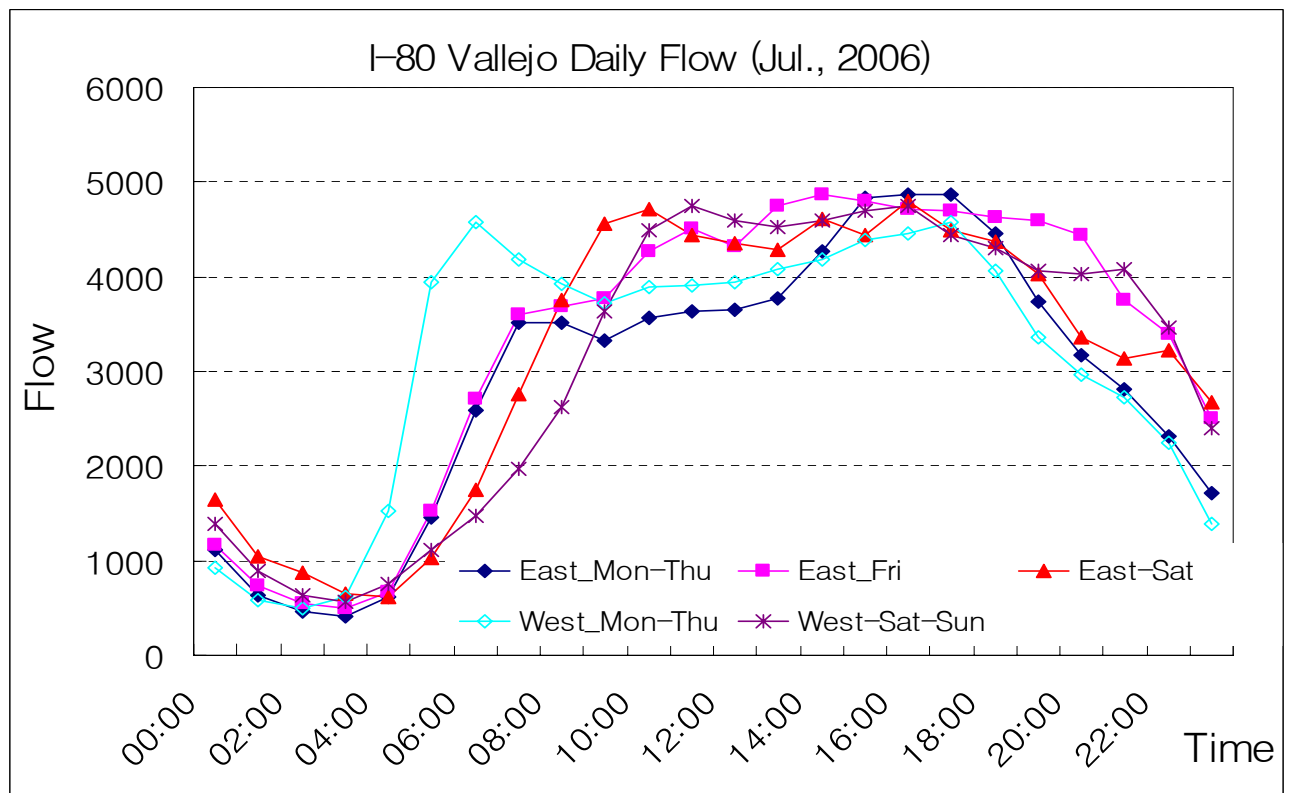


Figure 69: I-80 Vallejo (Tennessee Street) Daily Traffic Flow (PeMS)

7. IMPLEMENTATION CASE STUDIES

The *CA4PRS* software has been verified and applied on several Caltrans LLPRS projects, as summarized below.

7.1. VALIDATION ON I-10 POMONA

A case study was performed for the validation of *CA4PRS* on the first concrete LLPRS project on I-10 near Pomona. This job consisted of rebuilding 2.8 lane-km within one 55-hour weekend closure (Friday 10 p.m. – Monday 5 a.m.) in late 1999 (Figure 70). The highway segment, having four-lanes in each direction, was built in the early 1960s and had a high concentration of deteriorated concrete pavement due to traffic volumes of 240,000 ADT, approximately 9 percent of which were heavy trucks. Two of the four lanes remained open while the inner truck lane (T1) in the eastbound direction was rehabilitated. The outer truck lane (T2) was used for construction access. The contractor used the “PCC concurrent single-lane paving” method. Demolition and concrete paving occurred simultaneously to replace the 230 mm of old slab with a new slab using fast-setting concrete. Under the incentives/disincentives clause in the contract, the contractor was awarded a \$500,000 bonus payment for successful completion of the PCC rehabilitation within the 55-hour weekend closure.

The lower bound production of 2.8 lane-km, predicted with the confidence level of 68 percent in the *CA4PRS* probabilistic mode, was identical to the actual production performance monitored by the research team during the weekend closure. The contractor encountered the lower production limit of 2.8 lane-km only because of several resource problems, including a 4-hour main batch plant breakdown. The *CA4PRS* probabilistic analysis estimated a best case (upper bound) scenario of 3.4 lane-km production.

7.2. APPLICATION ON I-710 LONG BEACH

The *CA4PRS* software was next tested on an asphalt LLPRS project on I-710 in Long Beach. A 4.4-km stretch of the freeway (total of 26.3 lane-km) was rehabilitated with long-life AC pavement in eight 55-hour weekend closures, two weekends earlier than initially planned by Caltrans District 7 (Figure 71). First opened in 1952, this stretch of I-710 carries more than 164,000 ADT, including 13 percent heavy trucks during weekdays. The project had four FDAC sections located under the four bridge overpasses, where the existing PCC pavement structure was

excavated and removed to a depth of 625 mm, and replaced with 325 mm of AC. The pavement between the FDAC sections received 230 mm of CSOL. During construction, Caltrans applied “counter-flow” traffic controls with two lanes-by-two lanes on the traffic roadbed for the full closure of the construction roadbed so that the contractor had a full access to construction.



Figure 70: I-10 Pomona Project with Half-Closure during One 55-Weekend



Figure 71: I-710 Long Beach Project during Eight Repeated 55-Hour Weekends

For this scenario, *CA4PRS* estimated that the maximum production capability of a 55-hour weekend was about 1.3 km of the CSOL section and about 0.4 km of the FDAC section. Prior to starting construction, the *CA4PRS* analysis results confirmed that the contractor's goal of completing the main rehabilitation work in eight weekend closures was realistic. However, the *CA4PRS* analysis also warned that the contractor's initial plan of rehabilitating 0.8 km of two FDAC sections and 1.3 km of the CSOL section per weekend was overly optimistic. (This optimism may have been encouraged by an incentive provision that offered the contractor \$100,000 per unused weekend closure, capped at \$500,000.) The contractor revised the construction staging-plan based on the production levels recommended by the researchers.

The contractor's actual production performance measured in the construction monitoring study by the research team was within 5 percent of the *CA4PRS* production estimates. In addition, the number of demolition hauling trucks (an average of 10 trucks per hour) and hot mix asphalt delivery trucks (12 trucks per hour on average) predicted by *CA4PRS* was similar to the contractor's eventual fleet.

7.3. IMPLEMENTATION ON I-15 DEVORE

In October 2004, a 4.5-km stretch (a total of 17 lane-km) of badly deteriorated concrete truck lanes on I-15 in Devore was reconstructed with 290 mm of new slab and 150 mm of new asphalt-concrete (AC) base (Figure 72). Under high traffic volumes (110,000 ADT with about 10 percent heavy trucks), two truck lanes in one direction were rebuilt in only 210 hours (about 9 days) using a one-roadbed continuous closure with around-the-clock (24/7) construction operations, applying a counter-flow traffic system.

The concept of total cost, integrating closure schedule, road user cost, and construction and traffic handling costs, was used as the evaluation criteria for the most economic closure strategy. The *CA4PRS* software was used for scheduling analysis as a baseline. The demand-capacity model (Highway Capacity Manual), and macroscopic (FREQ) and microscopic (Paramics) traffic simulation models were utilized for traffic delay analysis. Caltrans decided to implement eight 72-hour weekday closures with round-the-clock operations based on the *CA4PRS* schedule analysis. The analysis demonstrated that the 72-hour closure scenario had 77 percent

less total closure time, 34 percent less road user cost, and 38 percent less agency cost when compared with the traditional nighttime closures (see Table 3).

The I-15 Devore project combined conventional construction materials and operations with state-of-practice technologies to expedite construction and minimize adverse traffic impact. The following construction, traffic, and project management strategies, with applicable state-of-practice features, were introduced:

- Accelerate construction process and schedules with special pavement materials, efficient staging-plans, and contractual incentives
- Mitigate traffic disruptions and delay impacts by increasing the capacity of construction work zone during the extended closures
- Provide real-time travel information through the construction work zone with the goal of reducing peak hour traffic demand to derive more diversion to detour routes or the change of traveler's trip pattern or modes
- Propagate project information to the public and capture the change of public perception to the "Rapid Rehab" approach with surveys

The benefits of accelerated reconstruction on this project were evaluated to reduce agency costs by 25 percent (\$6 million) and to save road users an estimated \$2 million in time-value, compared to those of traditional repeated nighttime closures. The implementation of the technologies and proactive public outreach reduced the maximum peak-hour delay by 50 percent during the extended closures with a total 20 percent traffic demand reduction. Pre- and post-construction traffic web surveys, with about 400 respondents, were conducted to examine the public perception of the Rapid Rehab approach. Most survey respondents showed initially strong reluctance to the extended closures. Among the respondents, 64 percent expressed an initial preference for the traditional nighttime or weekend closures, and 14 percent requested cancellation of the project. However, of the respondents to the post-construction survey, 70 percent expressed support for Rapid Rehab projects.

Table 3: Schedule, Delay, and Cost Comparison for I-15 Devore Closure Scenarios

Closure Scenario (1)	Schedule Comparison		Traffic Comparison ^a		Cost Comparison	
	Closure Number (2)	Closure Hours (3)	Road User Cost (\$M) (4)	Peak Delay (Minute) (5)	Agency Cost ^b (\$M) (6)	Total Cost ^c (\$M) (7)
1-Roadbed Continuous	2	400	5	80	15	20
72-Hour Weekday	8	512	5	50	16	21
55-Hour Weekend	10	550	10	80	17	27
10-Hour Nighttime	220	2,200	7	30	21	28
^a with assumption of 20 percent traffic demand reduction						
^b Engineer's re-estimate based on the unsuccessful first round of bid						
^c Total cost = Road user cost + Agency cost (per row)						



Figure 72: I-15 Devore Project with Two One-Roadbed Continuous Closures

8. TECHNICAL SUPPORT

The electronic version of this user manual in a PDF format is available in the CA4PRS help menu (Figure 51). More detailed information about the *CA4PRS* software and its application in California is available on the Caltrans website, <http://www.dot.ca.gov/research/roadway/ca4prs/index.htm> (see Figure 52) or Dr. E.B. Lee's home page at <http://www.ce.berkeley.edu/~eblee/CA4PRS.htm>.

For more technical information, the user might contact:

Dr. E.B. Lee: Associate Researcher and Principal Investigator

University of California at Berkeley – Institute of Transportation Studies

Phone (510) 665-3637; Email: eblee@berkeley.edu

or;

Kim Willoughby: SPTC coordinator and Research Manager

Washington State Department of Transportation

Phone (360) 705-7978; Email: WillouK@wsdot.wa.gov.

Each SPTC DOT has a state coordinator as listed in the following table.

Coordinator in the Contributed State DOT

State DOT	Name	Phone	E-mail
Caltrans	Michael Samadian	(916) 324-2048	michael_samadian@dot.ca.gov
MnDOT	Steve Barrett	(763) 797-3067	steven.barrett@dot.state.mn.us
TXDOT	Michael Murphy	(512) 465-3686	mmurphy@dot.state.tx.us
WSDOT	Linda Pierce	(360)-709-5470	piercel@wsdot.wa.gov

9. CA4PRS TERMS AND ABBREVIATIONS

9.1. CA4PRS TERMS

Analysis Window

Here the user selects and controls the input categories for the PCC analysis module including: Construction windows, Rehabilitation sequence with respect to lane closure tactics, Concrete curing time, Pavement cross section changes, and Truck lane width. For each input category, a drop-down list of values or check box options is available. To analyze and compare various options, the user chooses one or more variables. The asphalt (CSOL and FDAC) analysis windows also allow the user to enter estimated cooling times for each AC lift, or to choose the option to run the *MultiCool* module internally instead.

Concrete Mix Design (PCC):

In the PCC analysis module there are three default concrete mix designs to choose from: 4-, 8-, and 12-hour curing time mixes. Fast setting hydraulic cement concrete (FSHCC) or early-age strength Type III PCC products can quickly achieve traffic opening strengths of 2.8 MPa (400 psi) in California. A user-defined concrete curing time is also allowed in the model.

Concurrent Working Method (PCC):

In the PCC Concurrent working method, the demolition and paving activities of the rehabilitation proceed concurrently in parallel, each with its own construction access lane. The concurrent working method has single or double lane paving method as sub-options.

Construction Window:

The Construction window refers to the time frame rehabilitating a segment of the freeway from mobilization of the project until reopening the rehabilitated section to traffic. Three types of construction windows are explored in this analysis: weekend closure, continuous closure with continuous operation, and continuous closure with daytime operation.

Continuous Closure:

Continuous closure blocks several traffic lanes from the beginning to the end of the rehabilitation project. Two options are defined for the continuous closure: continuous closure/continuous operation in which the operation of the rehabilitation continues 24 hours (around the clock) with 2 or 3 shifts per day, and continuous closure/shift operation in which work occurs over 1 or 2 shifts per day in order to save operation cost from nighttime operations.

Cooling Time:

The time to cool the asphalt concrete layer from delivery temperature (149 °C =300 F) to the specified stop temperature (74 °C =165 F).

CSOL Rehabilitation Module:

The abbreviation of Crack Seal and AC Overlay is a typical asphalt concrete pavement rehabilitation strategy in the *CA4PRS* model. With this method, approximately 200 mm of hot mix asphalt concrete with 4 lifts will be placed on an existing cracked and sealed PCC pavement.

Deterministic Mode:

Constructability analysis with input parameters treated as fixed numbers (constants) without variation with time.

Double Lane Rehabilitation (FDAC):

In double lane AC rehabilitation, both truck lanes (T1+T2) are rebuilt in the same construction window instead of separating them into two separate weekend construction windows.

Double Lane Paving (PCC):

In double lane paving, both truck lanes (T1+T2) are rebuilt simultaneously instead of splitting into two separate construction windows for each lane.

Fast-Setting Hydraulic Cement Concrete (FSHCC):

Rapid strength gain concrete which achieves flexural strengths of 400 psi within 4 to 8 hours after placement.

FDAC (Full Depth AC) Replacement Module:

Another type of AC pavement rehabilitation strategy in the *CA4PRS* model. The existing pavement structure, the PCC slab, CTB, and part of the aggregate base are replaced with Full Depth AC (typically 6 lifts).

Full Closure (CSOL):

A CSOL rehabilitation working method, in which all lanes in one direction of the freeway (4 lanes) will be closed for rehabilitation at the same time.

Full Completion (CSOL / Half Closure):

A Half Lane Closure scenario for CSOL rehabilitation, where multiple lifts (4 lifts) are placed in all lanes during the weekend closure.

Half Closure (CSOL):

A type of CSOL rehabilitation working method in which half of the lanes in one freeway direction (typically two lanes) are closed while the other lanes are open to traffic. As soon as two lifts of AC paving are completed, traffic is switched to those lanes so that the other lanes may be paved.

Linear Scheduling Method or Line of Balance:

Linear scheduling is the planning and scheduling technique of the construction process with no more than one activity in the same location at the same time (in some cases, to ensure work continuity of crews).

When applied to a project with a geographically linear nature, such as highways, the technique has been called the linear scheduling method.

LLPRS:

The abbreviation for Caltrans Long Life Pavement Rehabilitation Strategies of which the objectives are to 1) provide 30+ years of service life, 2) require minimal maintenance, and 3) have sufficient production capability for 6 lane-km rehabilitation over a 55-hour weekend closure. In terms of paving materials, LLPRS consists of two categories of rehabilitations: concrete LLPRS and asphalt LLPRS.

MultiCool:

A numerical AC cooling time simulation program developed to predict the temperature profiles in multiple lifts of asphalt concrete.

Partial Completion (CSOL / Half Closure):

A Half Lane Closure working method for CSOL rehabilitation, in which only a part (typically the first two lifts) of the AC pavement profile (typically 4 layers) is placed in all lanes during the first weekend closure. The remaining two lifts are placed during the second weekend closure.

Pavement Cross Sections (PCC):

Three alternative new pavement cross sections – 203 mm (8-inch), 254 mm (10-inch), and 305 mm (12-inch) – are included in the PCC analysis module. The latter two PCC slab designs (254 mm or 305 mm) require replacing the existing base with a new thicker (150 mm) base. The user can also create a custom cross section profile if the default cross sections in the *CA4PRS* menu are not applicable for the project.

PCC Reconstruction Module:

Portland Cement Concrete rehabilitation strategy in the *CA4PRS* model, in which the old pavement is removed and then rebuilt with PCC slab and optional pavement base structure.

Project Details Window

The project details window prompts the user to input the basic textual information on a proposed project, including identifying project descriptions, route name, post (station) miles, location, etc. In the project objective cell the user specifies the project scope by typing in total lane-km (or mile) to be rehabilitated.

Resource Profile Window

The contractor's logistics and resource constraints are two of the most decisive factors in rehabilitation production, especially in fast-track urban highway rehabilitation where the space and access for construction equipment is often limited. The user inputs the number and capacity of the available equipment and plants.

Scheduling Window

The scheduling aspects of the project are categorized into three sub-groups: mobilization /demobilization variables, construction closures (windows), and activity lead-lag time relationships.

Sequential Working Method (PCC):

A concrete pavement rehabilitation method in which the demolition and paving activities of the rehabilitation cannot proceed simultaneously. Instead, the paving activity can start only after the demolition activity is finished. This scheme has single or double lane paving as sub-options.

Single Lane Paving (PCC):

In single lane paving, two truck lanes are rebuilt separately lane-by-lane over two separate weekend closures. The first truck lane is rebuilt during the first weekend closure, and the second truck lane is rebuilt on the second weekend closure.

Single Lane Rehabilitation (FDAC):

In single lane rehabilitation, paving is completed in one of the two truck lanes on the first weekend and then the adjacent lane is paved on the following weekend closure.

Probabilistic (Stochastic) Mode:

Constructability analysis with input parameters as random variables generated from a predefined PDF for each input parameter.

Weekend Closure:

The traffic lanes needing rehabilitation are closed for a 55-hour period over the weekend, i.e., from 10 p.m. Friday to 5 a.m. the following Monday.

9.2. CA4PRS ABBREVIATION

AB	Aggregate Base
A+B	Cost (A) + Schedule (B) contract
AC	Asphalt Concrete
ACB	Asphalt Concrete Base
ACP	Asphalt Concrete Pavement
ACPA	American Concrete Pavement Association
ADT	Average Daily Traffic
B-P	Batch Plant
CA4PRS	Construction Analysis for Pavement Rehabilitation Strategies
Caltrans	California Department of Transportation
CRCP	Continuous Reinforced Concrete Pavement
CSOL	Crack Seal and Overlay (Asphalt overlay)
c/l-km	Centerline lane km
CPM	Critical Path Method
CTB	Cement Treated Base
CWZ	Construction Work Zone
D-C	Demand Capacity
DOT	Department of Transportation
D-T	Dump Trucks
E-D-T	End Dump Truck
FDAC	Full-Depth Asphalt Concrete replacement strategy
FHWA	Federal Highway Administration
FSHCC	Fast Setting Hydraulic Cement Concrete
HMA	Hot Mixed Asphalt
HCM	Highway Capacity Manual
HVS	Heavy Vehicle Simulator
I/D	Incentive + Disincentive contract
IPRF	Innovative Pavement Research Foundation
ITS	Institute of Transportation Studies
JCP	Jointed Concrete Pavement
kph	Km per hour or mph (mile per hour)
LCB	Lean Concrete Base
LCCA	Life Cycle Cost Analysis
LLPRS	Long Life Pavement Rehabilitation Strategies

M-T	Concrete Mixer Truck
MCB	Moveable Concrete Barrier
MDI	Multiple-Document Interface
NAPA	National Asphalt Pavement Association
NB	North bound
O-D	Origin Destination
P1/P2	Passenger lane 1 and 2
PCC	Portland Cement Concrete
PCCP	Portland Cement Concrete Pavement
PDF	Probability Distribute Function
PRC	Pavement Research Center at U.C. Berkeley
RSC	Rapid Strength Concrete
RTF	Rich Text Format file
RUC	Road user cost
SB	South bound
S-B-T	Semi-Bottom Dump Truck
SD	Standard Deviation
SG	Subgrade
SHOP	State Highway Operation Protection
SPTC	State Pavement Technology Consortium (CA, MN, TX, WA DOT)
SQL	Sequel Sever Language
T1/T2	Track lane 1 and 2
TMP	Traffic Management Plan
TRB	Transportation Research Board
UCB-ITS	University of California at Berkeley-Institute of Transportation Studies

APPENDIX 1: CA4PRS TRAINING WORKSHOP

A.1.1: CA4PRS TRAINING WORKSHOP OVERVIEW

The *CA4PRS* workshop (2-day hands-on training) primarily focuses on the integration analysis of urban freeway rehabilitation under high traffic volume by taking into account long-life pavement performance, construction productivity, and road user inconvenience. The *CA4PRS* program helps agencies determine rehabilitation strategies that maximize production schedules and minimize agency costs and traffic delays. It becomes an especially powerful tool when combined with traffic simulation models. *CA4PRS* has been utilized on several high-traffic urban freeway rehabilitation projects, including the I-710 Long Beach and I-15 Devore projects, and the program has demonstrated its effectiveness through maximized construction scheduling resulting in millions of dollars in savings in agency and road user costs.

This *CA4PRS* training workshop focuses on the application of the *CA4PRS* software program to achieve the primary goal of obtaining the best estimate of the length of freeway that can be rehabilitated or reconstructed within the project constraints. Although the software is relatively easy to use, the end user should fully understand all background assumptions and calculation logics as well as a reasonable range of input parameters to apply the software as a scheduling and production analysis tool for actual highway projects. The training workshop provides all information about the software, i.e., background, application, implementation, and integration. In addition, this workshop helps transportation agencies find a better balance between pavement design, construction, and traffic delay from the total costs perspective in the planning of highway rehabilitation and reconstruction projects.

Additional topics Included in the training workshop are: traffic delay impact analysis to calculate the work-zone road user cost on the network level based on the traffic measurement and macro and microscopic simulations; and evaluation of construction and traffic scenarios for pavement reconstruction projects based on the economic total cost concept.

This is a two-day interactive hands-on training workshop focusing on the software (*CA4PRS*) demonstration and computer lab course exercises using actual sample projects. The trainees learn how to run the *CA4PRS* software program as a construction scheduling tool for urban freeway rehabilitation/reconstruction projects. They also learn how to combine and integrate the construction scheduling analysis results with traffic delay impact analysis on the urban network during reconstruction.

The target audience includes: state highway agencies, especially during the planning and design stages when the information can optimize pavement, construction and traffic scenarios; and design/planning engineers, construction engineers, traffic engineers, consultants, and paving contractors, especially during estimating and project control stages.

The instructor, Eul-Bum (E.B.) Lee (Ph.D., PE, PMP), has more than 15 years of various experiences in highway construction, including structural design, project control and claims, and academic research. As a research engineer currently working in the Institute of Transportation Studies at the University of California at Berkeley, he has focused research on the management of highway infrastructures rehabilitation. Dr. Lee earned M.E. and Ph.D. degrees in the Engineering Project Management Program at the University of California at Berkeley.

Prior to commencing doctoral study, he gained 10 years of experience coordinating international mega projects in Asia, Europe, and North America. He is actively involved in the academic and professional communities in transportation engineering, serving as a committee member and journal reviewer for the American Society of Civil Engineers (ASCE), the Association of American State Highway and Transportation Officials (AASHTO), and the Transportation Research Board (TRB). His research work has been published in a variety of professional civil engineering society and transportation journals.

A.1.2: CA4PRS LAB EXERCISE

Example 1: PCC Rehabilitation

Caltrans is developing a construction management plan to rebuild a 5 centerline-km section of Interstate 15 in Ontario. The freeway has 4 lanes each direction and the two (inner and outer) truck lanes are to be reconstructed. In other words, the *total project objective = 20 lane-km*, consisting of 5 km x 2 truck lanes x 2 directions. The old pavement structure has the 205 mm (8") PCC slab, the 100 mm (4") cement treated base (CTB), and 205mm (12") Aggregate Base (AB). The new pavement cross-section is: 305 mm (12") new slabs with the 12-hour curing-time of early age strength Type III PCC and 150 mm (6") new AC base. Dowel bars and tie bars will be installed in the new jointed concrete pavement. The new outer truck lane is 14' widened. As the project engineer, you are required to compare the rehabilitation schedules utilizing the CA4PRS model (deterministic approach) for the following 4 closure scenarios:

- **Construction Windows:**
 - 55-hour weekend closures (Friday 10PM – Monday 5 AM)
 - 72-hour weekday closures (Tuesday 12 AM ~ Friday 12 AM)
- **Lane Closure Tactics:**
 - Sequential single-lane reconstruction (two lanes closed)
 - Concurrent double-lane reconstruction (full closure with counter-flow traffic)

Please answer the following questions for each rehabilitation scenario to fill out the comparison table below:

- What is the maximum construction production, i.e., how many lane-km could be finished within a closure?
- How many closures in total are needed to finish the whole project, and what is the total duration of the closures?

Please report your analysis results to the class **within 1 hour** by filling out the following comparison table.

Closures	Method	Production per closure (lane-km)	Total closure numbers	Total closure duration (hours)
55-hour Weekend	Sequential			
	Concurrent			
72-hour Weekday	Sequential			
	Concurrent			

Example 2: CSOL Rehabilitation

Caltrans is developing a construction management plan to rehabilitate a 9 centerline-km section of Interstate 710 in Compton, which has from 3 up to 6 lanes each direction. The old pavement structure has the 205 mm (8”) PCC slab and the 100 mm (4”) cement treated base (CTB). As the CSOL rehabilitation strategy, the existing PCC slabs will be Cracked and sealed, and AC overlaid with a total of 225mm (9”). The suggested lift profile from the bottom is: 50mm (2”) of AR-8000, 75mm (3”) of AR-8000, 75 mm (3”) of PBA-6a, and 25 mm (1”) of Open grade friction course.

The full closure of one roadbed with “counter-flow traffic”, as lane closure tactics during construction, is considered to rehabilitate the 3 main lanes together with the median (8’ width) and outside (10’ width) shoulders.

As the project engineer, you are required to analyze the rehabilitation schedules with 55-hour weekend closures (Friday 10PM – Monday 5 AM), utilizing the CA4PRS model.

Please answer the following questions for each rehabilitation scenario to fill out the comparison table below:

- What is the maximum construction production, i.e., how many centerline-km could be rehabilitated for each 3, 4, and 5 lane section during one 55-hour weekend closure?
- How many closures in total are needed to finish the whole project assuming that one section (3-5 lanes) has about 3 centerline-km of distance each, and what is the total duration of the project?

Please report your analysis results to the class **within 1 hour** by filling out the following comparison table.

Lane per direction (distance)	Production per closure (centerline- km)	Total closure numbers	Total closure duration (hours)
3 lanes (3 centerline-km)			
4 lanes (3 centerline-km)			
5 lanes (3 centerline-km)			

Example 3: FDAC Rehabilitation

Caltrans is developing a construction management plan to rehabilitate a 5 centerline-km section of Interstate 5 in Orange. The freeway has 4 lanes each direction, and the two (inner and outer) truck lanes are to be replaced. In other words, the total project objective = 20 lane-km, consisting of 5 km x 2 truck lane x 2 directions. The old pavement structure has the 205 mm (8") PCC slab and the 100 mm (4") cement treated base (CTB). As the FDAC replacement strategy, a total of new AC 375 mm (15") will replace the old concrete pavement structure. The suggested lift profile from the bottom is: 50mm (2") of AR-8000 working platform, 3 x 75mm (3") of AR-8000, 75 mm (3") of PBA-6a, and 25 mm (1") of Open grade friction course.

The full closure of one roadbed with "counter-flow traffic", as lane closure tactics during construction, is used. As the project engineer, you are required to compare the rehabilitation schedules utilizing the CA4PRS model (deterministic approach) for the following 2 closure scenarios:

- 55-hour weekend closures (Friday 10PM – Monday 5 AM)
- 72-hour weekday closures (Tuesday 12 AM ~ Friday 12 AM)

Please answer the following questions for each rehabilitation scenario to fill out the comparison table below:

- What is the maximum construction production, i.e., how many lane-km could be finished within a closure?
- How many closures in total are needed to finish the whole project, and what is the total duration of the closures?

Please report your analysis results to the class **within 1 hour** by filling out the following comparison table.

Closures	Production per closure (lane-km)	Total closure numbers	Total closure duration (hours)
55-hour Weekend			
72-hour Weekday			

APPENDIX 2: PRE-EVALUATION QUESTIONNAIRE

A.2.1: ACRONYM DEFINITION

Describe what the following words (acronym) stand for.

No	Acronym	Description
1	AWIS	Automated Work Zone Information Systems
2	CA4PRS	Construction Analysis for Pavement Rehabilitation Strategies
3	CPM	Critical Path Method
4	CSOL	Crack and seat (PCC and AC) OverLay
5	CTB / LCB	Cement Treated Base / Lean Concrete Base
6	CWZ	Construction Work Zone
7	FDAC	Full Depth AC (Replacement)
8	FSHCC	Fast Setting Hydraulic Cement Concrete
9	HCM	Highway Capacity Manual
10	HMA	Hot Mix Asphalt
11	LLPRS	Long-Life Pavement Rehabilitation Strategies
12	MCB	Moveable Concrete Barriers
13	RSC	Rapid Strength Concrete
14	RUC	Road User Cost
15	SPTC	State Pavement Technology Consortium

A.2.2.: YOUR EVALUATION OF WORKSHOP

1. Overall workshop content and format well organized?

Disagree Strongly 1 2 3 4 Agree Strongly 5

2. Instructors expressed ideas clearly and used workshop time effectively?

Disagree Strongly 1 2 3 4 Agree Strongly 5

3. Workshop material was presented at appropriate level for me?

Disagree Strongly 1 2 3 4 Agree Strongly 5

4. Workshop facility and arrangements were suitable?

Disagree Strongly 1 2 3 4 Agree Strongly 5

5. Your expectations for the workshop were well met?

Disagree Strongly 1 2 3 4 Agree Strongly 5

6. I would recommend this workshop to others?

Disagree Strongly 1 2 3 4 Agree Strongly 5

7. What did you like best about the workshop?

8. What did you like least about the workshop?

9. Any suggestions for the next Introductory Workshop?

A.2.3: ACRONYM QUESTIONNAIRE

Describe what the following words (acronym) stand for.

No	Acronym	Description
1	AWIS	
2	CA4PRS	
3	CPM	
4	CSOL	
5	CTB / LCB	
6	CWZ	
7	FDAC	
8	FSHCC	
9	HCM	
10	HMA	
11	LLPRS	
12	MCB	
13	RSC	
14	RUC	
15	SPTC	



Construction Analysis for Pavement Rehabilitation Strategies Software Integration of Design, Construction, and Traffic for Accelerated Highway Rehabilitation Projects

Increasingly, state transportation agencies are shifting focus from new construction to the rehabilitation and reconstruction of existing highways. Urban highway rehabilitation projects often create undesirable congestion, safety problems, and limited access for users who depend on the transportation facility. The question of how to economically rebuild deteriorating highways in metropolitan areas, while minimizing disruptions to the public and surrounding business is a challenging task for state transportation agencies.

One innovation in the effort to reduce highway construction time and its impact on traffic is CA4PRS (Construction Analysis for Pavement Rehabilitation Strategies), a scheduling software tool designed to help planners and designers select economical rehabilitation strategies. Developed by The Institute of Transportation Studies (ITS) at the University of California at Berkeley (UCB) with a FHWA pooled-fund grant sponsored by the State Pavement Technology Consortium (California, Minnesota, Texas, and Washington state departments of transportation), CA4PRS estimates the maximum distance and duration of highway rehabilitation or reconstruction projects under a given set of project constraints, including schedule interfaces, pavement design, construction logistics, and traffic operations.

Benefits of CA4PRS

CA4PRS is designed to identify optimal rehabilitation solutions that balance on-schedule construction production, traffic inconvenience, and agency costs. Additional benefit is realized when CA4PRS results are integrated with macroscopic and microscopic traffic simulation tools for estimating road user delay costs that arise from construction. During the design and construction

phases of highway rehabilitation projects, CA4PRS helps transportation agencies, contractors, and consultants:

- develop staging construction plans,
- establish CPM schedules,
- estimate cost (A) + schedule (B) contracts, and
- calculate incentive/disincentive specifications.

Validation and Implementation

Since 1999, CA4PRS has been successfully implemented on high traffic volume urban freeway rehabilitation projects in California and other sponsoring states. The software was validated on the 2.8 lane-km I-10 Pomona project, where it was used for the estimation of slab replacement using fast-setting hydraulic cement concrete completed in one 55-hour weekend closure. The software was also used to develop a construction staging plan for the I-710 Long Beach project, where 26 lane-km of asphalt concrete was reconstructed in a series of eight 55-hour weekend closures—two weekends ahead of schedule.

More recently, the tool was used with traffic simulation models to select the most economical rehabilitation scenario for the I-15 Devore project. The 4.5-km reconstruction project, which would have taken 12 months using traditional nighttime closures, was completed over two 9-day periods using single roadbed continuous closures and around-the-clock construction. This “rapid rehab with accelerated construction” approach saved 25 percent (\$6 million) in agency costs and significantly reduced road user costs.

CA4PRS was also used by Washington State DOT engineers to explore rapid rehabilitation strategies on two projects: Interstate 5

A collaboration of the following agencies:

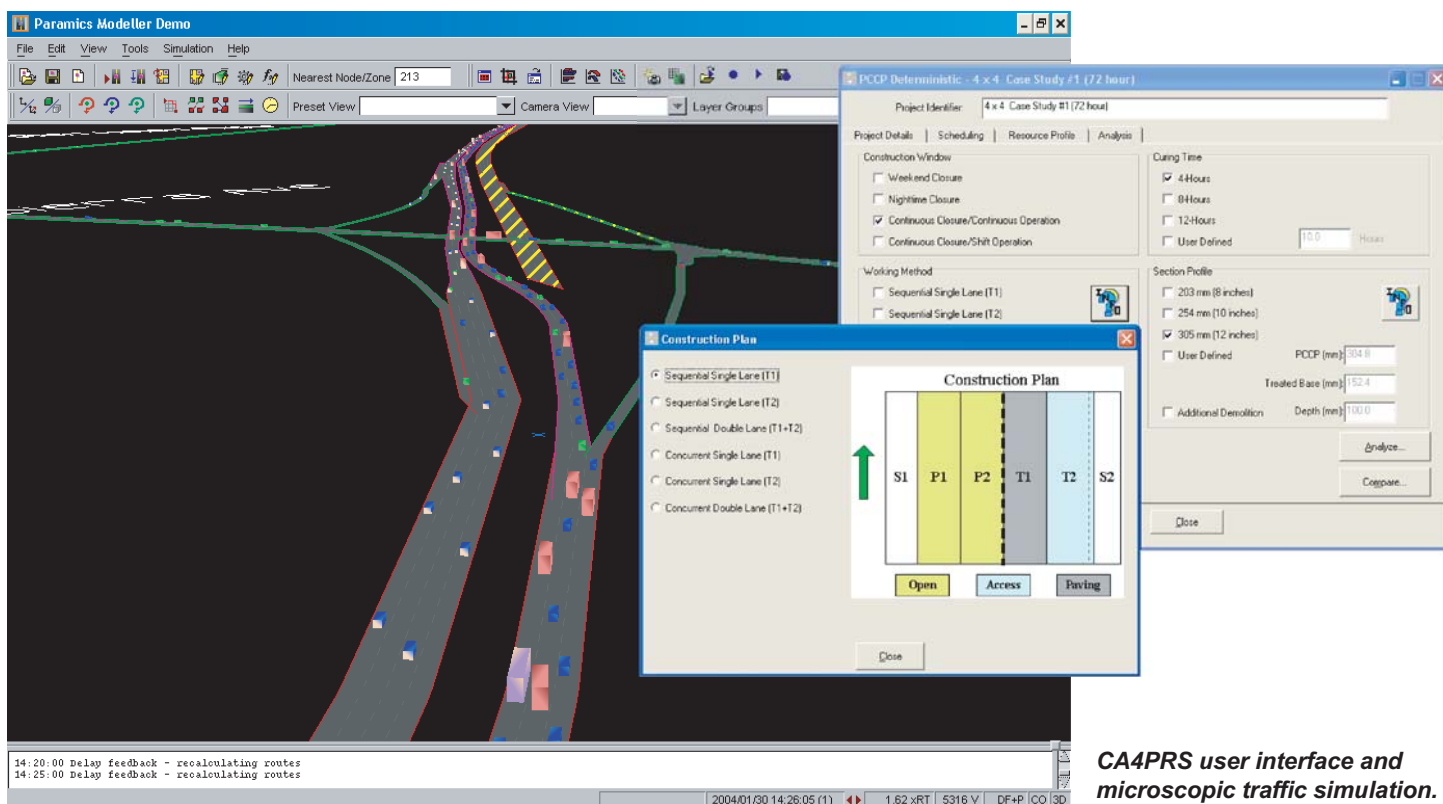


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CA4PRS user interface and microscopic traffic simulation.

(I-5) in Federal Way (Seattle), where a 3-mile section will be replaced with PCC over asphalt base; and the reconstruction of a portion of southbound I-5 beneath the Convention Center in Seattle. This section is one of the highest volume locations in Washington State and is currently under construction using a scheme of four weekend closures.

In 2004, the Minnesota Department of Transportation (MNDOT) implemented CA4PRS on two resurfacing projects. Both jobs involved milling and bituminous paving: one was a nighttime operation on Interstate 494, and the other was a combination of night and complete weekend closures on Interstate 393.

Outreach

CA4PRS has been presented at national conferences and workshops hosted by the Transportation Research Board (TRB), American Association of State Highway Transportation Officials (AASHTO), and the Federal Highway Administration (FHWA), and described in transportation journal articles in TR News, and the American Concrete Paving Association (ACPA) and National Asphalt Pavement Association (NAPA) industry newsletters. Hundreds of CA4PRS posters and brochures have been distributed to potential users, and information on the software is available on the Caltrans and UC Berkeley websites.

Training workshops are being provided to pavement and traffic engineers in the contributing states. Over the last three years, about 400 transportation engineers in the sponsoring DOTs have attended 2-day intensive training seminars conducted by the primary developer of CA4PRS, Dr. E.B. Lee.

Enhancement

CA4PRS is being upgraded to improve user friendliness, add more rehabilitation strategies, and integrate with traffic simulation models. CA4PRS interim Version 1.1 will improve input interfaces, including the development of a manual to help users understand background logic, analysis processes, and the relationships of the input variables. Version 1.5 will be expanded to cover more rehabilitation features, such as the rehabilitation of continuously reinforced concrete pavement (CRCP) and dowel-bar retrofits.

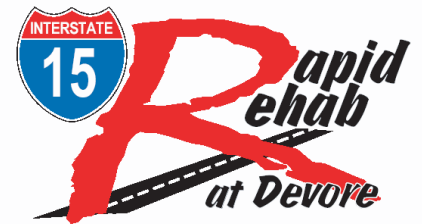
In the update for the CA4PRS Version 2.0 the schedule analysis will be integrated with traffic simulation tools such as the demand-capacity model based on Highway Capacity Manual to calculate road user delay in the construction work zone, and to estimate agency construction and traffic handling costs. Eventually the concept of the total cost (as the sum of agency and road user costs) based on the scheduling, traffic, and cost analyses will be provided to select the most economical highway rehabilitation scenarios.

For More Information

Michael Samadian, Caltrans Division of Research and Innovation
phone: (916) 324-2048
e-mail: michael_samadian@dot.ca.gov

Dr. E.B. Lee, University of California at Berkeley
Institute of Transportation Studies
phone: (510) 665-3637
email: eblee@berkeley.edu

On the Web:
<http://www.dot.ca.gov/research/roadway/ca4prs/ca4prs.htm>



'Rapid Rehab' Accelerated Urban Highway Reconstruction: I-15 Devore Project Experience

Since 1998, the California Department of Transportation (Caltrans) has been implementing a Long-Life Pavement Rehabilitation Strategies (LLPRS) program to address the need for cost effective approaches to rebuilding 2,800 lane-km of aging pavements in the urban highway network. This case study presents an innovative fast-track reconstruction approach applied to a heavily trafficked LLPRS project on Interstate-15 (I-15) in Devore in southern California. A 4.5-km stretch of badly damaged concrete truck lanes was rebuilt in only two 210-hour (about 9 days) one-roadbed continuous closures (called "extended closures" hereafter), using counter-flow traffic and 24-hour operations. The same project would have taken 10 months using traditional nighttime closures.

Innovations adopted for this groundbreaking "Rapid Rehab" project also included:

- **Automated Work Zone Information Systems (AWIS)** to update travelers with the real-time travel information
- **Quickchange Moveable Barrier (QMB)** system with a dynamic lane configuration to minimize traffic disruption

- **Mix design of rapid strength concrete (RSC)** to enable the project to be opened to traffic 12 hours after placement,
- **Web-based information systems** for disseminating project updates and surveying public perception,
- **Incentive/disincentive provisions** to encourage the contractor to complete the closures on time, and
- **Multifaceted outreach program** to gain public support.

Engineers on the project used CA4PRS (Construction Analysis for Pavement Rehabilitation Strategies) incorporated with traffic simulation models to arrive at an optimal and economical rehabilitation closure scenario, construction schedule, and traffic management plan. The post-construction data validated the analysis and simulation estimates of productivity and traffic delay.

As a result of AWIS and public outreach, a 20 percent reduction in traffic demand through the construction work zone (CWZ) was achieved, thereby reducing the maximum peak-hour delay by 50 percent (45 minutes instead of the expected 90 minutes).



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Figure 1. Location of project.

Surveys on the project website showed dramatic changes in public perception of the 'Rapid Rehab' approach of the extended closures from initial reluctance and objection to positive support.

Advantages of using this method of fast-track accelerated reconstruction included: a shorter period of disruption for the traveling public, 30-year life expectancy for the new pavement, improved safety for motorists and workers, and a 25 percent reduction in construction costs (\$6 million savings) when compared to traditional repeated nighttime closures.

PRE- AND POST-CONSTRUCTION EVALUATION

The I-15 Devore corridor has consistently high weekday commuter peaks and even higher volume (120,000 ADT) on weekends, when leisure travelers in the Los Angeles area often travel to and from Las Vegas and to resort locations along the Colorado River. The project scope was to rebuild a 4.5 km stretch of the damaged concrete slabs and base pavements with a new cross-section of 290-mm doweled slabs using rapid strength concrete and 150-mm AC base on top of the remaining aggregate base or native material. The I-15 northbound roadbed was closed for reconstruction first, switching traffic to the southbound side through median crossovers at the ends of the work zone. The

two directions of traffic shared the southbound lanes as "counter-flow traffic" separated by QMB. The same process was repeated for the reconstruction of the southbound direction.

The pre-construction analysis sought the most economical reconstruction closure scenario while integrating the competing concerns of construction schedule, traffic impacts, and agency cost. Four construction closure scenarios — 72-hour weekday, 55-hour weekend, one-roadbed continuous (24 hours per day, seven days per week), and 10-hour nighttime — were compared. The pre-construction analysis concluded that the extended closure was the most economical scenario.

Compared to traditional 10-hour nighttime closures, the extended closure scenario had about 80 percent less total closure time, about 30 percent less road user cost due to traffic delay, and about 25 percent less agency cost for construction and traffic control. Rehabilitation constructability issues comparing pavement design and material alternatives were reviewed from the perspective of production scheduling and traffic inconvenience. CA4PRS analysis was used to identify the costs associated with road user traffic delay in order to determine appropriate incentives and disincentives for the construction contract.

As a result of high project bids from the first round of construction bidding, the initial rehabilitation scope to reconstruct both truck lanes was altered to include reconstruction of only the outer truck lane and targeted slab replacement on the inner truck lane. The consequence of a five percent traffic volume increase as construction was delayed from spring to fall 2004 was significant: the estimated road user cost increased by 90 percent (from \$5 million to \$9.5 million) and the estimated maximum peak-hour queue delay increased from 75 to 90 minutes.

Contractor production rates exhibited a significant learning curve. The majority of the reconstruction operations during the southbound reconstruction (later in the project) showed 28 percent more rapid progress for slab removal and 22 percent more rapid progress for paving than those of the northbound reconstruction (earlier in the project). The continuous lane reconstruction on the outer truck lane had twice the productivity of the random slab replacement operation on the inner truck lane.

WORK ZONE TRAFFIC CONTROL

Use of QMB, at a cost of about \$1.5 million for one month's rental, helped to balance traffic impacts to commuters and weekend travelers by providing a dynamic lane configuration with one additional lane converted temporarily from the rehabilitated AC shoulder. The barrier was moved twice a day to accommodate peak directional traffic.

The Devore project represents the first implementation of AWIS in California for LLPRS projects. The system played a useful

role in informing motorists of real-time travel and detour route information. AWIS travel estimate information was posted on the permanent and temporary changeable message signs (CMS) that were strategically located at key decision points for roadway users. The information was also posted on the traffic roadmap on the project website as part of an interactive public outreach campaign. Surveys conducted on the project website indicated that the majority (72 percent) of visitors found the project information on the web useful for their trip planning. The impact of reconstruction closures on traffic was "acceptable" according to a traffic measurement study and web surveys conducted during and after the construction. The maximum peak delay was measured at about 75 minutes on weekends (northbound) and 45 minutes on weekdays (southbound) during the extended closures, compared to the predicted 90 minutes delay during weekdays with the assumption of a 10 percent reduction. The traffic demand through the CWZ was greatly reduced by diverting it to major freeway detour routes. I-10 eastbound was used as the I-15 northbound detour and showed 10 percent daily traffic volume increase with a peak of 36 percent in the morning peak hours. I-215 southbound was used as the I-15 southbound detour and showed about 15 percent daily volume increase. A total of 20 percent traffic demand reduction through the CWZ (15 percent more than the initial expectation) due to diversion and travel time changes was attributed to public outreach and automated traffic control efforts.

The I-15 Devore project combined conventional construction materials and operations with state-of-practice technologies to

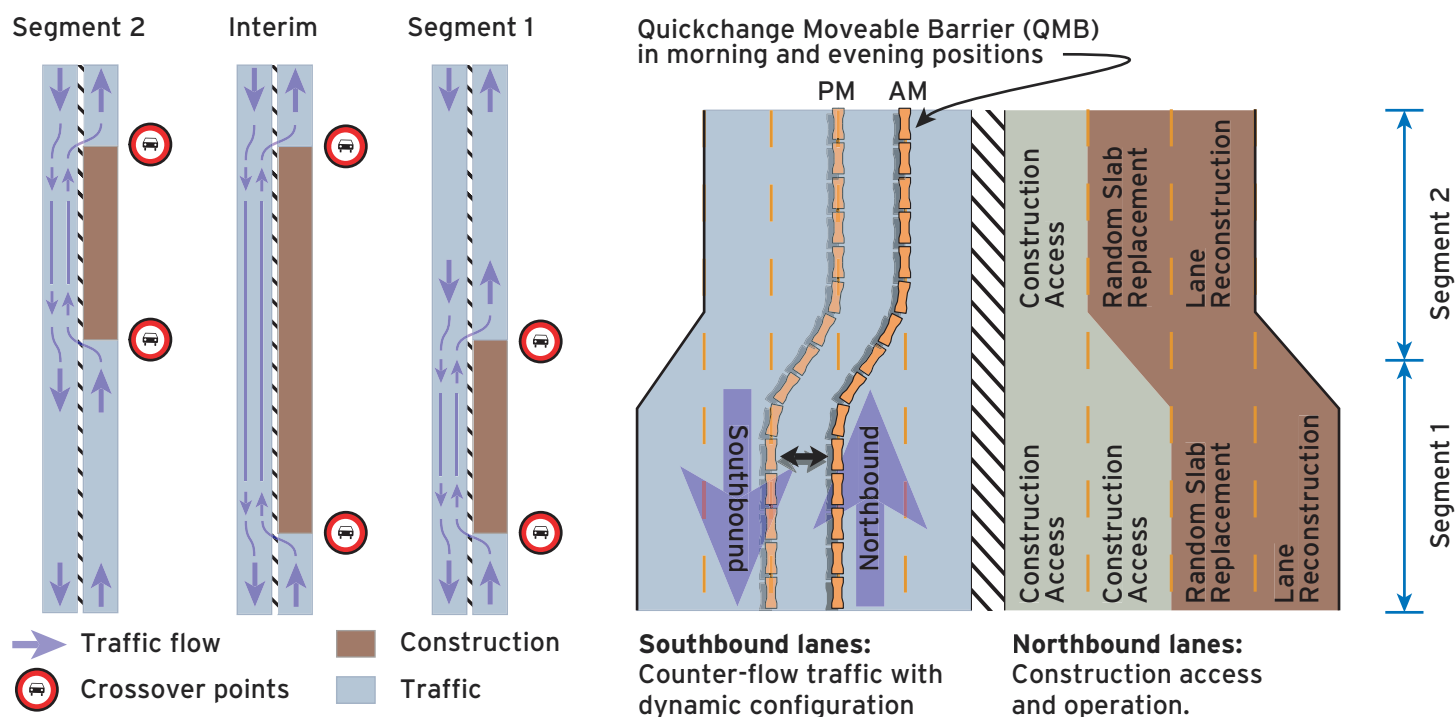


Figure 2. Dynamic lane configuration during northbound reconstruction; pattern was reversed for southbound lane reconstruction.

expedite construction and minimize adverse traffic impact. Additional features of the project which contributed to traffic control were:

- **A project command center** facilitated department coordination with other agencies and disciplines (construction, design, traffic, and public affairs) and monitored traffic and construction remotely on CCTV.
- **Caltrans shared information and received constructive feedback** from the local community through the High Desert Commuter Advisory Committee (HDCAC).
- **Caltrans funded a free commuter bus service** to promote ridesharing at a cost of \$65,000 with 14 buses from the High Desert to the south, which increased ridership by 40 percent.
- **The Construction Zone Enhanced Enforcement Program (COZEEP)** cost \$300,000 and was implemented with a total of 1,034 traffic citations issued during one month of construction by the California Highway Patrol.
- **The Freeway Service Patrol (FSP)** service removed 1,243 disabled vehicles from the CWZ at a cost of about \$100,000.



Figure 3. Automated Work Zone Information System (AWIS) framework.

OUTREACH AND PUBLIC PERCEPTION

To achieve the goal of 20 percent reduction in traffic demand, Caltrans implemented an extensive public outreach program. Outreach materials included a comprehensive project brochure, construction flyers, a construction advisory electronic bulletin, fast-fax through email, a project information help hotline, and several public meetings for local communities. The project website was created with the cooperation of local agencies and the surrounding three Caltrans District Offices (Los Angeles, Orange, and San Diego) to provide up-to-date comprehensive project information. The project website had a total of about 100,000 views for three months before and during the extended closures and played an important role in gaining input from the public.

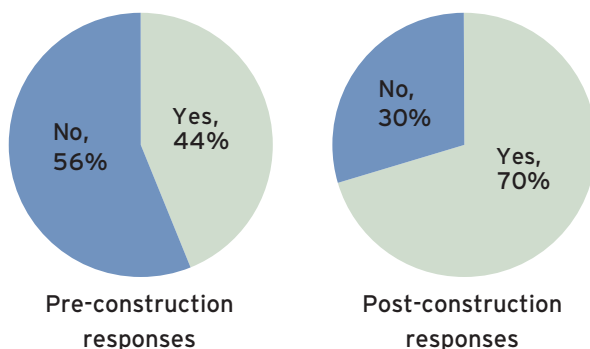


Figure 4. Change in public perception to support 'Rapid Rehab' construction.

Pre- and post-construction traffic web surveys were conducted to examine the public perception of the 'Rapid Rehab' approach. Of 400 pre-construction respondents, 64 percent expressed an initial preference for the traditional nighttime or weekend closures and 14 percent even requested to cancel the project. However, public perception substantially changed because of the public outreach efforts. Of the post-construction respondents, 70 percent expressed support for 'Rapid Rehab' projects. This result indicates that with the expectation of the benefits from accelerated project completion, the public is willing to bear increased construction cost in exchange for reduced construction schedules, thus mitigating the inconvenience of traffic disruption.

MORE INFORMATION

On the Web:

<http://www.dot.ca.gov/research/roadway/roadway.htm>

David K. Thomas, Design Chief (Design C)
 Caltrans District 8
 T: (909) 384-4118
 E: david_k_thomas@dot.ca.gov

Dr. E.B. Lee, Principal Investigator
 University of California at Berkeley
 Institute of Transportation Studies
 Pavement Research Center

T: (510) 665-3637
 E: eblee@berkeley.edu

Computer Simulation Model: Construction Analysis for Pavement Rehabilitation Strategies

Eul-Bum Lee¹ and C. W. Ibbs²

Abstract: Most state highways in the United States were built during the 1960s and 1970s with an infrastructure investment of more than \$1 trillion. They now exceed their 20 year design lives and are seriously deteriorated. The consequences are high maintenance and road user costs because of degraded road surfaces and construction work zone delays. Efficient planning of highway rehabilitation closures is critical. This paper presents a simulation model, Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS), which estimates the maximum amount of highway rehabilitation/reconstruction during various closure timeframes. The model balances project constraints such as scheduling interfaces, pavement materials and design, contractor logistics and resources, and traffic operations. It has been successfully used on several urban freeway rehabilitation projects with high traffic volume, including projects on I-10 and I-710. The CA4PRS helps agencies and contractors plan highway rehabilitation strategies by taking into account long-life pavement performance, construction productivity, traffic delay, and total cost.

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CE Database subject headings: Pavements; Reconstruction; Rehabilitation; Constructability; Computer aided simulation; Simulation models.

Introduction

Paradigm Change in Highway Construction

About 256,000 km of the National Highway System, which is 4% of the American road network (U.S. Census Bureau 1994), carries 40% of auto travel and 75% of truck traffic. It also connects 90% of the households and businesses in the nation (FHWA 1996). Many of the pavements on these highways, constructed during the infrastructure construction boom in the 1960s and 1970s, have exceeded their design lives in less than 20 years due to continuously increasing traffic demand. This is evidenced by the fact that over the last 20 years highway traffic has increased by 75% while highway facilities have expanded by only 4% during the same period (Herbsman and Glagola 1998).

In recent years state transportation agencies have shifted their focus from building new transportation facilities to “4R” projects: restoration, resurfacing, rehabilitation, and reconstruction. This shift in emphasis was driven by studies which show that maintaining federal-aid highways in their current physical condition has a financial rate of return of about 30–40%, while constructing

new highways has a rate of return generally lower than 10% (U.S. Congressional Budget Office 1988). Further complicating rehabilitation project is that roughly 30% of these 4R type highway rehabilitation projects were located in urban areas in 1999–2001, where construction caused serious problems with traffic service for the communities that used these freeways (WisDOT 2002).

Innovative Highway Rehabilitation in California

The State of California, a pioneer in highway construction, is facing deteriorated highway infrastructure on a large scale. More than 90% of the 78,000 lane/km of the state highway system was built between 1955 and 1970 with 20 year design lives. This significant state of degradation adversely affects road-user safety and ride quality, and causes high vehicle operating and highway maintenance costs. In 1998, the California Department of Transportation (Caltrans) initiated the Long-Life Pavement Rehabilitation Strategies (LLPRS) program to rebuild approximately 2,800 lane/km of deteriorated urban freeways over the next 10 years. The program represented an estimated \$1 billion investment over and above the regular State Highway Operation and Protection budget (Caltrans 1998). The LLPRS candidate projects were selected based upon criteria of poor pavement structural condition and ride quality and a minimum 150,000 average daily traffic (ADT) or 15,000 average daily truck traffic. Most of the candidate freeways were Portland cement concrete (PCC) paved interstates in the Los Angeles Basin (80%) and the San Francisco Bay Area (15%).

Traditionally, urban freeway rehabilitation or reconstruction projects in California have used 7 or 10 h nighttime closures because daytime closures cause unacceptable delays to weekday peak travel. The disadvantage of nighttime closures is that they may lead to poor construction quality control which, in turn, may affect pavement life expectancy and pavement surface smoothness, and jeopardize the safety of road users and construction crews (Lee 2000). Nighttime closures may also result in longer

¹Research Engineer, Univ. of California at Berkeley, Institute of Transportation Studies, Building 452 (PRC), 1353 S. 46th St., Richmond, CA 94804. E-mail: eblee@berkeley.edu

²Professor, Dept. of Civil & Environmental Engineering, Univ. of California at Berkeley, 213 McLaughlin Hall, Berkeley, CA 94720. E-mail: ibbs@ce.berkeley.edu

Note. Discussion open until September 1, 2005. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on February 11, 2004; approved on June 10, 2004. This paper is part of the *Journal of Construction Engineering and Management*, Vol. 131, No. 4, April 1, 2005. ©ASCE, ISSN 0733-9364/2005/4-449–458/\$25.00.

total closure times, higher construction and traffic handling costs, and greater traffic delay to road users. In recognition of these drawbacks, Caltrans has adopted innovative highway rehabilitation strategies of accelerated construction with continuous (round-the-clock) operations during 55 h weekend or 72 h weekday closures for LLPRS projects.

Research Motivation and Approach

The increased need for highway maintenance and rehabilitation has led to much research on construction methods and their impact on traffic flow. However, no systematic research has been conducted, until now, with the goal of integrating pavement materials and design, construction logistics, and traffic operations. These issues are clearly essential to determine the most economical rehabilitation strategies (Anderson and Russell 2001). For rehabilitation of high volume urban freeways, three competing goals should be satisfied:

- the pavement should have a service life of at least 30 years,
- construction schedules should be fast, and
- traffic delays resulting from construction closures should be minimized.

To meet design life and constructability goals, pavement design must focus on: (1) thinner structural sections and (2) materials and curing times that can shorten construction without sacrificing quality and performance (Roesler et al. 1999). Construction planning should focus on hastening the construction process and making it more predictable by incorporating such concepts as contingency (risk) management, incentives/disincentives (*I/D*), and cost plus schedule (*A+B*) bidding (Arditi et al. 1997). Traffic planning should focus on minimizing traffic delay impact without sacrificing construction productivity.

The integrated analysis of design, construction, and traffic requires a construction production analysis model to provide a schedule baseline for highway rehabilitation projects. The Construction Analysis for Pavement Rehabilitation Strategies (*CA4PRS*) software, described in this paper, is such a scheduling tool and was designed for constructability analysis of highway rehabilitation projects (Technology/Business Opportunity: *CA4PRS* 2003). It is a knowledge-based computer simulation model designed to help transportation agencies and paving contractors make sound construction project management decisions at each stage of the highway rehabilitation project: planning, design, and construction.

The input variables of *CA4PRS* are schedule interfaces, pavement design and materials, resource constraints, and lane closure schemes. These were identified by experienced Caltrans engineers and the research team. The model's formulation was reviewed and adjusted through technical committee meetings with the Southern California Chapter of the National Asphalt Pavement Association and the Western States Chapter of the American Concrete Pavement Association. The software was tested on projects throughout California. Such tests also allowed us to gather construction resource and schedule activity relationship data to calibrate and validate the software. Details of these case studies are described later in this paper.

Research Relevance and Applicability

The *CA4PRS* model was developed to provide road agencies and the transportation industry with a systematic construction engineering and management tool for the rehabilitation and reconstruction of highways. The model is beneficial for the highway

agencies especially during the planning and design stages when the resulting analysis can be used to optimize pavement, construction, and traffic operations. It is also useful for design and construction engineers, consultants, and paving contractors in providing cost savings by comparing various alternatives during estimating and project control stages.

Software Overview

The *CA4PRS* is a production analysis tool designed to estimate the maximum probable length of highway pavement that can be rehabilitated or reconstructed given the various project constraints (Lee 2000). As summarized in Table 1, the *CA4PRS* model evaluates "what-if" scenarios with respect to rehabilitation production by comparing the following input variables (alternatives):

1. pavement strategy: PCC reconstruction, crack and seat PCC and asphalt overlay (CSOL), or full-depth asphalt concrete replacement (FDAC);
2. construction window: nighttime closures, weekend closure, continuous closure, or combinations of the above;
3. lane closure tactics: number of lanes to be closed for rehabilitation (i.e., partial or full closures);
4. material constraints: mix design and curing time for concrete or cooling time for asphalt;
5. pavement cross section: thickness of new concrete or asphalt concrete;
6. concrete pavement base types: lean concrete base or asphalt concrete base (ACB);
7. contractor's logistical resource constraints: location, capacity, and numbers of rehabilitation equipment available (batch plant, delivery and hauling trucks, paving machine); and
8. scheduling interfaces: mobilization/demobilization, traffic control time, and activity lead-lag time relationships, and buffer sizes.

A powerful feature of *CA4PRS* is that it can be integrated with macro- and microscopic traffic simulation models to quantify road user costs during construction. This can help planners, designers, and construction and materials engineers determine which pavement materials/structures and rehabilitation strategies maximize production without creating unacceptable traffic delays. The rehabilitation strategies and associated input variables modeled in *CA4PRS* are described in the following sections.

Rehabilitation Strategies Modeled

It is challenging yet necessary to define a typical or common pavement rehabilitation process when trying to model the process. There are numerous rehabilitation strategies that may be implemented and are contingent upon: pavement materials, lane closure tactics, and contractor's resource constraints. Consultation with agencies and contractors led us to focus on and incorporate three common rehabilitation strategies into *CA4PRS*:

1. PCC reconstruction: remove the old pavement and rebuild with PCC slab and optional pavement base structure;
2. CSOL rehabilitation: crack and seat the old PCC pavement and overlay with new asphalt-concrete (AC) pavement; and
3. FDAC replacement: remove the old pavement and replace with full-depth AC pavement.

The number of traffic lanes in one direction of a typical urban freeway was assumed to be four for the sake of simplicity. Since most passenger lanes (*P1* and *P2*) are generally in good condi-

Table 1. Categorized Major Parameters, Comparable in Construction Analysis for Pavement Rehabilitation Strategies Model

Category	Options	
Rehabilitation strategies	Concrete rehabilitation or reconstruction Portland cement concrete (PCC) Asphalt concrete	Crack seal and overlay (CSOL) Full depth ac (FDAC) replacement
Pavement cross section	PCC	203 mm slab 305 mm slab User defined cross section
	CSOL and FDAC	Multiple lift of layers
Scheduling constraints	Construction windows	Nighttime closure Weekend closure Continuous closure
	Schedule relationship	Mobilization/demobilization Activity lead-lag relationship
	Curing time (PCC)	4 h (fast-setting cement) 12 h (Type III PCC) User specified curing time
	Cooling time (CSOL and FDAC)	Function lift thickness and weather
Lane closures and rehabilitation sequences	PCC	Concurrent work method Sequential work method
	PCC and FDAC	Single-lane rehabilitation Double-lane rehabilitation
	CSOL	Partial closure Full closure
Contractor's logistics and resource constraints	Demolition hauling trucks	Capacity and number per hour
	Paving material delivery trucks	Capacity and number per hour
	Batch plant	Capacity and number
	Paving machines	Speed and number

tion, it furthermore was assumed that only the two outer truck lanes (T_1 and T_2) will be rebuilt in each direction in the PCC reconstruction and FDAC replacement strategies, as per LLPRS practice. In the case of CSOL rehabilitation, the whole freeway (i.e., main traffic lanes including median and outside shoulder) is assumed to be subject to rehabilitation. Details on rehabilitation methodologies and design variables for each rehabilitation strategy as an individual module in *CA4PRS* are summarized below.

Portland Cement Concrete Reconstruction Strategy

Pavement Design Alternatives

The PCC reconstruction module in *CA4PRS* incorporates the following pavement design-related criteria (Lee et al. 2000):

- new pavement cross-sections,
- concrete mix design for new PCC slab, and
- the width of the outside truck lane.

Three alternative new pavement cross sections—203 mm (8 in.), 254 mm (10 in.), and 305 mm (12 in.)—are included in the PCC analysis module. The existing slab is assumed to be 203 mm thick (typical California situation). The latter two PCC slab designs (254 or 305 mm) will require replacing the existing base with a new thicker (150 mm) base, as illustrated in Fig. 1. The user can also create his/her own cross-section profile if the default cross sections in the *CA4PRS* menu are not applicable for the project. The user can also enter in any additional demolition depth that might be necessary to comply with new height clearance requirements for bridge underpasses or overpasses.

In the PCC analysis module there are three default concrete mix designs to choose from: 4, 8, and 12 h curing time mixes.

Fast setting hydraulic cement concrete or early-age strength Type III PCC products can quickly achieve traffic opening strengths of 2.8 MPa (400 psi) in California. This allows extra paving time that cannot be attained when using ordinary PCC. A user-defined concrete curing time is also allowed in the model.

The user has two options for the width of a new outside truck lane (T_2): regular width (3.7 m) tied to the concrete shoulder, or widened truck lane (4.3 m).

Reconstruction Methodologies

Four combinations of construction operation sequence and lane closure tactics are included in the PCC analysis module: concurrent single-lane, sequential single-lane, concurrent double-lane, and sequential double-lane rehabilitations. The concurrent methods refer to the simultaneous undertaking of demolition of the existing slab and new slab and base paving operations. In the sequential methods slab paving starts only after the demolition and base paving are completed. When performing both operations concurrently, interruptions between construction equipment (e.g., loader, hauling trucks, paving machine, and delivery trucks) can be avoided or minimized by providing the demolition and paving activities with their own access lane. In the sequential methods the demolition and paving activities share one lane for construction access one after the other, thus leaving one more lane open for freeway traffic than in the concurrent scenario. The shoulder is not assumed to be a reliable access lane in urban environments because it may be less than 3 m wide, adjacent to sound walls, or not continuous.

The two existing truck lanes can be paved either one by one or both lanes at once. Both single-lane paving and double-lane reha-

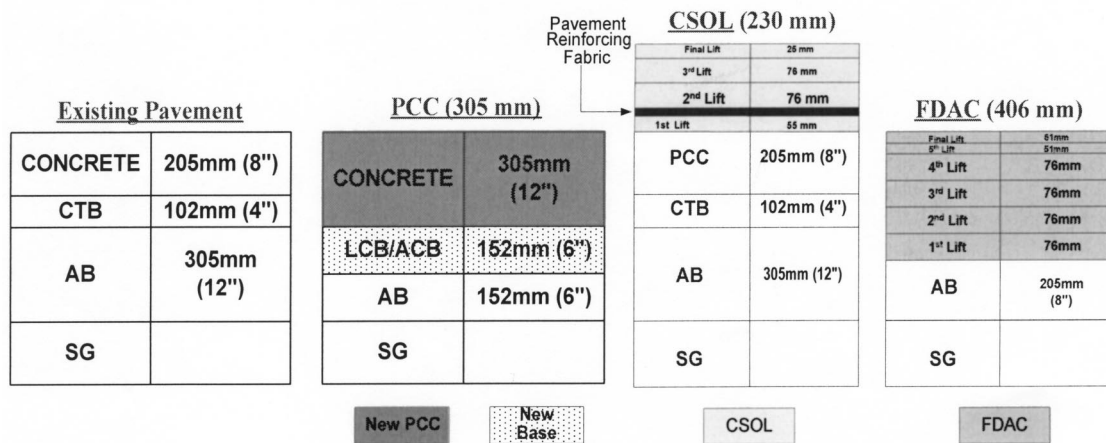


Fig. 1. Typical pavement cross-section changes modeled in Construction Analysis for Pavement Rehabilitation Strategies

bilitation are applicable for both concurrent and sequential methods. Washington State Department of Transportation reported that higher productivity was observed when two lanes were paved simultaneously (Washington State Department of Transportation 2002). Double lane paving may have other advantages: simpler installation of tie bars and better quality control and long-term performance in the longitudinal joint.

Crack and Seat Portland Cement Concrete and Asphalt Overlay Rehabilitation Strategy

Pavement Design Alternatives

In California, the crack seat and asphalt concrete overlay (CSOL) rehabilitation involves placing three to five new AC layers on top of the cracked and seated PCC pavement. To slow the propagation of cracks, it is a common practice to install a pavement reinforcing fabric saturated with tack coat while the first AC layer is still hot. The CSOL's major advantage is that it does not require removal of the existing PCC slabs, unlike the PCC reconstruction or FDAC replacement strategy. However the AC overlay cannot be placed underneath bridge overpasses unless there is adequate clearance between the freeway and the bridge. Another constraint is that CSOL usually requires that all lanes and shoulders be paved to maintain uniform elevation.

In the CSOL analysis module the user is able to create a project-specific cross section by specifying the total number of AC layers (lifts) required and the thickness of each layer. As illustrated in Fig. 1, the typical Caltrans LLPRS design calls for four AC layers with thickness varying from 200 mm (8 in.) to 250 mm (10 in.). "MultiCool" is a numerical simulation program that calculates the AC cooling time for multi layer AC paving. It is embedded in CA4PRS to check the suspension of the paving operation due to the cooling time (Timm et al. 2001).

Rehabilitation Methodologies

Two lane closure tactics are permitted in the CSOL analysis module: CSOL full-closure and CSOL half-closure (Lee et al. 2002a).

In the case of CSOL full closure, one direction of the freeway is completely closed off for rehabilitation and traffic is switched to the other side of construction through median crossovers, utilizing counter-flow traffic. The main lanes and shoulders are overlaid completely layer by layer and lane by lane on one side of the freeway within a closure. Usually the paving operation alternates the sequence of paving lanes to minimize waiting time.

Half-closure CSOL requires closing down only two out of four lanes in one direction during a closure. This allows two lanes to be open to traffic in the direction of the rehabilitation and four lanes of traffic in the opposite direction. Traffic would be separated from the construction work zone by a moveable concrete barrier. This half-closure option has two suboptions: (1) CSOL half closure with full completion, where part of the AC layers are placed on two lanes, and then traffic is shifted to the newly paved lanes while the other two are paved, and this process is repeated until the section is completed; and (2) CSOL half-closure with partial completion, where the first bottom AC layers are overlaid at the first closure and the remaining top layers are completed at the subsequent closure.

Full Depth Asphalt Concrete Replacement Strategy

The FDAC replacement strategy requires complete removal of the PCC and partial trimming of the aggregate base to accommodate the specified depth of the new AC pavement. Similar to the CSOL analysis module, the FDAC analysis module allows the user to input project-specific AC cross sections. In Caltrans LLPRS projects a rich bottom AC layer will normally be placed on top of the recompacted aggregate base (AB), followed by five or six AC layers paved sequentially, with total thickness ranging from 330 mm (13 in.) to 406 mm (16 in.), as illustrated in Fig. 1.

The FDAC analysis module includes two lane closure tactics: single-lane or double-lane rehabilitation. A benefit of the double-lane rehabilitation is that the multiple AC layers are interlocked by overlapping the longitudinal joints between adjacent lanes. The single- and double-lane rehabilitation concept for the FDAC replacement is similar to the PCC reconstruction methodology. Following a common AC paving practice, the double-lane rehabilitation option for the FDAC replacement does not specify paving both lanes in one pull, unlike PCC reconstruction.

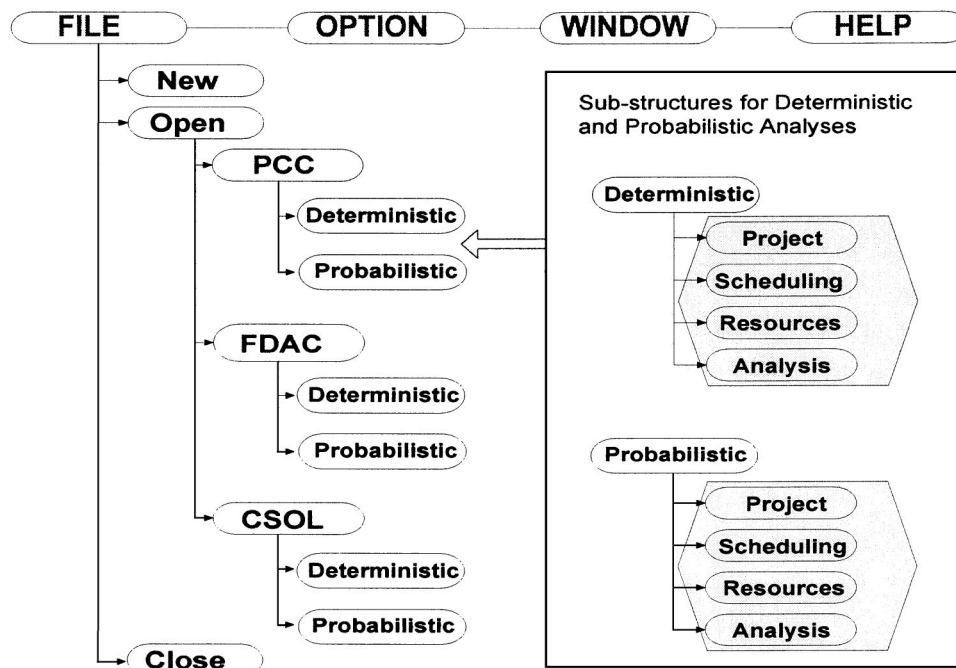


Fig. 2. Construction Analysis for Pavement Rehabilitation Strategies menu structure and analysis hierarchy

Construction Analysis for Pavement Rehabilitation Strategies Computational Background

Construction Analysis for Pavement Rehabilitation Strategies Computational Process

Typical input procedure and analytical processes of *CA4PRS* are:

1. choose the analysis mode: deterministic or probabilistic.
2. Input the total scope (lane km) of the rehabilitation project.
3. Select a rehabilitation strategy: PCC reconstruction, CSOL rehabilitation, or FD AC replacement analysis modules.
4. Define the new pavement cross section: slab and base thickness (PCC) or layer profile (AC).
5. Set the concrete curing time (PCC) or AC cooling time (or let the *MultiCool* software calculate cooling times interactively).
6. Decide a construction window (closure timing and length): for example, 10 h nighttimes, 55 h weekend, or 72 h week-day closures.
7. Define activity lead-lag relationships (start to start, finish to start, etc.) between major operations: mobilization, demobilization, and minimum time interfaces between operations.
8. Select rehabilitation sequences and lane closure tactics: concurrent versus sequential and single-lane versus double-lane rehabilitations.
9. Input contractor's logistical resources (crew, equipment, and plants) for major operations. The number of hauling and delivery trucks per hour should take into account the minimum cycle for supply and haul trucks. (Our prior research has found that loading or discharging trucks is usually the critical productivity constraint). Based on the preceding inputs and constraints, *CA4PRS* performs the following computations and continues as follows:
10. Quantify material volumes for the major operations: demolition, AC paving, or PCC paving.
11. Utilize a simplified critical path method (CPM) scheduling analysis to calculate available durations for the main operations.

12. Quantify the production capability of each resource input, and apply a linear scheduling technique to identify the constraining resource and consequently the maximum production capability.
13. Provide consistency checks on the main *CA4PRS* outputs including:
 - maximum rehabilitation production (lane kilometer) per closure,
 - total number of closures and duration needed to finish the whole project scope,
 - constraining resource and minimally needed resource profile, and
 - balanced time allocation between the demolition and paving operations.

Construction Analysis for Pavement Rehabilitation Strategies Computational Platform

The *CA4PRS* software runs on Microsoft Windows 95/NT4.098/2000/XP™ or higher operating systems. It is developed in *Microsoft Visual Basic 6.0* and utilizes a Microsoft Access 2000 database as the back-end for data storage, though it does not require Microsoft Access installed to run the software. The *CA4PRS* utilizes a number of third-party, royalty free tools to enhance the user friendliness, versatility of the user interfaces, and presentation quality of the program. It has a multiple-document interface, similar to Microsoft Excel or Microsoft Word, which enables multiple projects and analyses to be opened, viewed, and compared simultaneously. The *CA4PRS* is designed for project level analysis and each project analysis must have a unique identifier as the primary key in the *CA4PRS* database for storing and retrieving all related information.

As illustrated in Fig. 2, *CA4PRS* employs a systematic menu structure that groups menu items in an intuitive manner and provides context sensitive online help and a user manual. Its hierarchical structure provides extensive graphical and tabular outputs

and incorporates a report feature that documents the analysis input and output for printing or saving as an Adobe Portable Document Format or Rich Text Format file. The *CA4PRS* provides seamless transition between deterministic and probabilistic analysis modes, as described in the following section, and the user can easily transfer project data between the two analysis modes.

Deterministic and Probabilistic Analysis Modes

The *CA4PRS* can perform both deterministic and probabilistic analysis. In the deterministic analysis mode the input parameters including resource and scheduling constraints (activity lead-lag time relationships) are treated as constants without any variations. This mode seeks the straightforward maximum pavement amount (distance) that can be rebuilt within the construction closure windows under the given project constraints.

The probabilistic (stochastic) mode treats input parameters as random variables. Each variable can be described using an appropriate statistical distribution; the options are uniform, normal, log normal, beta, geometric, triangular, truncated normal, and truncated log normal. This mode permits the user to review the likelihood of achieving different pavement rehabilitation production rates, utilizing Monte Carlo simulation.

Construction Analysis for Pavement Rehabilitation Strategies Input Windows

The user starts an analysis by either creating a new one or by opening an existing one, with four input tab window prompts:

- project details window,
- scheduling window,
- resource profile window, and
- analysis window.

The input configurations of the deterministic and stochastic modes are similar except that the former asks the user to specify absolute values for the uncertain variable (constant numbers). The stochastic model provides the user a list library of probability distribution functions to choose from.

Project Details Window

The project details window prompts the user to input the basic textural information on a proposed project, including identifying project descriptions, route name, post (station) miles, location, etc. In the project objective cell the user specifies the project scope by typing in total lane kilometer (or mile) to be rehabilitated. This user-specified project objective (goal) then acts as the baseline to compute total number of closures required based on the rehabilitation production estimation of each scenario to be calculated at the end of the analysis. When a number of alternative scenarios are considered for the same project, the distinct features of each alternative can be recorded under the “Project Notes” portion of the window.

Scheduling Window

Fig. 3 shows the probabilistic scheduling window (with the PCC analysis module shown for example). The scheduling aspects of the project are categorized into three subgroups: mobilization/demobilization variables, construction closures (windows), and activity lead-lag time relationships. A certain minimum time will

be needed for mobilization and demobilization purposes such as site preparation, cleaning up, and, more importantly, traffic control for the construction.

As illustrated in Fig. 3, three alternative time frames (construction windows) are available to the user: nighttime (typically weekdays), weekend, and continuous closures. The continuous closure has two sub-options to choose from: (1) continuous closure with daytime-only shift operations, with one or two crew shift(s) for a limited number of weekdays while the freeway remains closed throughout the whole period of rehabilitation; and (2) continuous closure with continuous operations, which means fast-track accelerated construction with round-the-clock operations using two or three rotating crew shifts.

Resource Profile Window

The contractor's logistics and resource constraints are two of the most decisive factors in rehabilitation production, especially in fast-track urban highway rehabilitation where the space and access for construction equipment is often limited. The user inputs the number and capacity of the available equipment and plants. Some resource inputs will require prior knowledge, experience, and personal judgment from the user. For instance, the user should input a reasonable number of demolition hauling trucks per hour by taking account of the expected loading cycle time of the demolition and turn-around time of the trucks between site and dumping area.

Analysis Window

Fig. 4 illustrates the analysis window. Here the user selects and controls the following input categories for the PCC analysis module, as an example:

- construction windows,
- rehabilitation sequence with respect to lane closure tactics,
- concrete curing time,
- pavement cross section changes, and
- truck lane width.

For each input category, a drop-down list of values or check box options is available. To analyze and compare various options, the user can choose one or more variables. The asphalt (CSOL and FDAC) analysis window also allows the user to enter estimated cooling times for each AC lift or choose the option to run the *MultiCool* software instead.

Construction Analysis for Pavement Rehabilitation Strategies Outputs

As mentioned earlier, *CA4PRS* produces either a single or multitude of analysis results, depending on the number of input options the user selects. For example, if the user elects to consider two concrete curing time options (4 and 12 h), two rehabilitation sequence options (sequential single lane and concurrent double lane), and two cross section profiles (203 mm and user defined) for the 55 h weekend closure in the PCC analysis module, a total of eight ($2 \times 2 \times 2$) analysis results, each in a separate output window, will be generated once the user clicks the “Analyze” button.

Deterministic Outputs

In deterministic mode, the output is presented in two parts: “Production Details” and “Production Chart”. Included in the produc-

Constructability and Productivity Analysis
File Options Window Help

PCCP Probabilistic - I-15 72-H Weekday (Final)

Project Identifier: I-15 72-H Weekday (Final)

Project Details | Scheduling | Resource Profile | Analysis

Mobilization
Mobilization (Hours): 3.0 ✓

Demobilization (Hours): 13.7 ✓

Construction Start Date: 3 / 1 / 2004

Construction Window...

Lag Times for Sequential Working Method
Demolition to New Base Installation (Hours): 14.0 ✓

PCCP Installation can begin before New Base Installation is Complete: ☐

New Base Installation to PCCP Installation (Hours): 6.0 ✓

Lag Times for Concurrent Working Method

Construction Window Settings

Weekend Closure
Start Time on Friday: 10:00 PM
End Time on Monday: 05:00 AM
Available Hours: 55.0

Nighttime Closure
Start Time on First Day: 07:00 PM
End Time on Next Day: 05:00 AM
Available Hours per Day: 10.0

Continuous Closure/Continuous Operation
Start Time on First Day: 12:00 AM
No. of Continuous Work Days: 3.0
Available Hours per Day: 24.0

Continuous Closure/Shift Operation
Daily Start Time: 06:00 AM
No. of Continuous Work Days: 6.0
Available Hours per Day: 16.0

Save

Save Close

Fig. 3. Scheduling input window in Portland cement concrete probabilistic mode

tion details screen are the user input summary and the main analysis results (see Fig. 5). The main results are the maximum production of each rehabilitation scenario analyzed in terms of lane kilometer, and the total number of closures to finish the whole rehabilitation project scope (objective) based on the maximum production of the each scenario. Some additional information is also provided in the outputs, including a summary of material volumes for the major operations like demolition, slab paving, and base paving. The main results of the CPM scheduling analysis are provided as well; i.e., the optimally balanced maximum duration of the demolition and paving activities within a given closure time limit. The production chart screen contains a "line of balance schedule" where the linear progress of the main rehabilitation operations is plotted against the time.

One of the most useful features of the *CA4PRS* outputs, especially from the contractor's point of view, is identifying which input equipment constrains the operations. A list of input resources, with a comparison of the input number and number minimally needed, is tabulated in the project details output window (see Fig. 5).

When the user checks multiple options in each category in the analysis window, the number of output windows could be too large for effective comparison of all the analyzed scenarios at once. To avoid this inconvenience, a simplified comparison table can be generated. It summarizes the main inputs and outputs in a hierarchical manner: starting with the construction window, then the cross section profile, the rehabilitation sequence, etc.

Probabilistic Outputs

One main difference between the probabilistic and deterministic modes is that the probabilistic outputs shows a plot of the distribution of maximum production as a result of the Monte Carlo simulation (see Fig. 5). The probabilistic output, as a normalized distribution according to the Central Limit Theorem (Moder et al. 1983), represents the most likely maximum production as a mean, and productions at -0.5 SD and $+0.5$ SD as lower and upper bounds, respectively. Despite requiring more input information and more time to run, the stochastic formulation provides a more realistic estimation and comprehensive description of the rehabilitation production. One other advantage of the probabilistic analysis is that it permits the user to see the relative contribution of the probabilistic input variables to the rehabilitation production as a whole, in the sensitivity "tornado" chart.

Construction Analysis for Pavement Rehabilitation Strategies Case Studies

The *CA4PRS* software has been verified and applied on several numbers of Caltrans LLPRS projects, as summarized below.

Construction Analysis for Pavement Rehabilitation Strategies Validation on I-10 Project

A case study was performed for the validation of *CA4PRS* on the first concrete LLPRS project on Interstate 10 near Pomona. This

PCCP Deterministic - I-15 72-H Weekday (Final)

Project Identifier: I-15 72-H Weekday (Final)

Project Details | Scheduling | Resource Profile | Analysis

Construction Window

☐ Weekend Closure

☐ Nighttime Closure

☒ Continuous Closure/Continuous Operation

☐ Continuous Closure/Shift Operation

Working Method

☐ Sequential Single Lane (T1)

☐ Sequential Single Lane (T2)

Curing Time

☐ 4-Hours

☐ 8-Hours

☒ 12-Hours

☐ User Defined 10.0 Hours

Section Profile

☐ 203 mm (8 inches)

☐ 254 mm (10 inches)

☐ 305 mm (12 inches)

☒ User Defined

PCCP (mm): 290.0

Treated Base (mm): 152.4

☐ Additional Demolition

Depth (mm): 100.0

Analyze...

Compare...

Close

Construction Plan

☒ Sequential Single Lane (T1)

☐ Sequential Single Lane (T2)

☐ Sequential Double Lane (T1+T2)

☐ Concurrent Single Lane (T1)

☐ Concurrent Single Lane (T2)

☐ Concurrent Double Lane (T1+T2)

Construction Plan

S1 P1 P2 T1 T2 S2

Open Access Paving

Close

Fig. 4. Analysis input window in Portland cement concrete deterministic mode

job consisted of 2.8 lane km successfully rebuilt with one 55 h weekend closure (Friday 10 p.m.–Monday 5 a.m.) in late 1999 (Lee et al. 2002b). The highway segment, having four lanes in each direction, was built in the early 1960s and had a high concentration of deteriorated concrete pavement due to traffic volumes of 240,000 ADT with approximately 9% heavy trucks. Two of the four lanes remained open while the inner truck lane (T1) in the eastbound direction was rehabilitated. The outer truck lane (T2) was used for construction access. The contractor used the “PCC concurrent single-lane paving” method. Demolition and concrete paving occurred simultaneously to replace the 230 mm of old slab with a new slab using fast-setting concrete. Under the incentives/disincentives clause in the contract, the contractor was awarded a \$500,000 bonus payment for successful completion of the PCC rehabilitation within the 55 h weekend closure.

The lower bound production of 2.8 lane km, predicted with the confidence level of 68% in the CA4PRS probabilistic mode, was identical to the actual production performance monitored by the research team during the weekend closure. The contractor encountered the lower production limit of 2.8 lane km only because of several resource problems, including a main batch plant breakdown for about 4 h. The CA4PRS probabilistic analysis estimated a best case (upper bound) scenario of 3.4 lane km production.

Construction Analysis for Pavement Rehabilitation Strategies Application on I-710 Project

The CA4PRS software was next tested on an asphalt LLPRS project on Interstate 710 in Long Beach, Calif. A 4.4 km stretch of the freeway (total of 26.3 lane km) was rehabilitated successfully with long-life AC in eight 55 h weekend closures, two weekends earlier than initially planned by Caltrans District 7 (Lee et al. 2003). First opened in 1952, this stretch of I-710 carries more than 164,000 ADT, including 13% heavy trucks during weekdays. The project had four FDAC sections located under the four bridge overpasses, where the existing PCC pavement structure was excavated and removed to a depth of 625 mm, and replaced with 325 mm of AC. The pavement between the FDAC sections received 230 mm of CSOL. During construction, Caltrans applied “counter-flow traffic” controls (“full-closure and full-completion AC rehabilitation” method).

For this scenario CA4PRS estimated that the maximum production capability of a 55 h weekend was about 1.3 km of the CSOL section and one FDAC section (about 0.4 km). Prior to starting construction, the CA4PRS analysis results confirmed that the contractor’s goal of completing the main rehabilitation work in eight weekend closures was realistic. However, the CA4PRS analysis also warned that the contractor’s initial plan of rehabili-

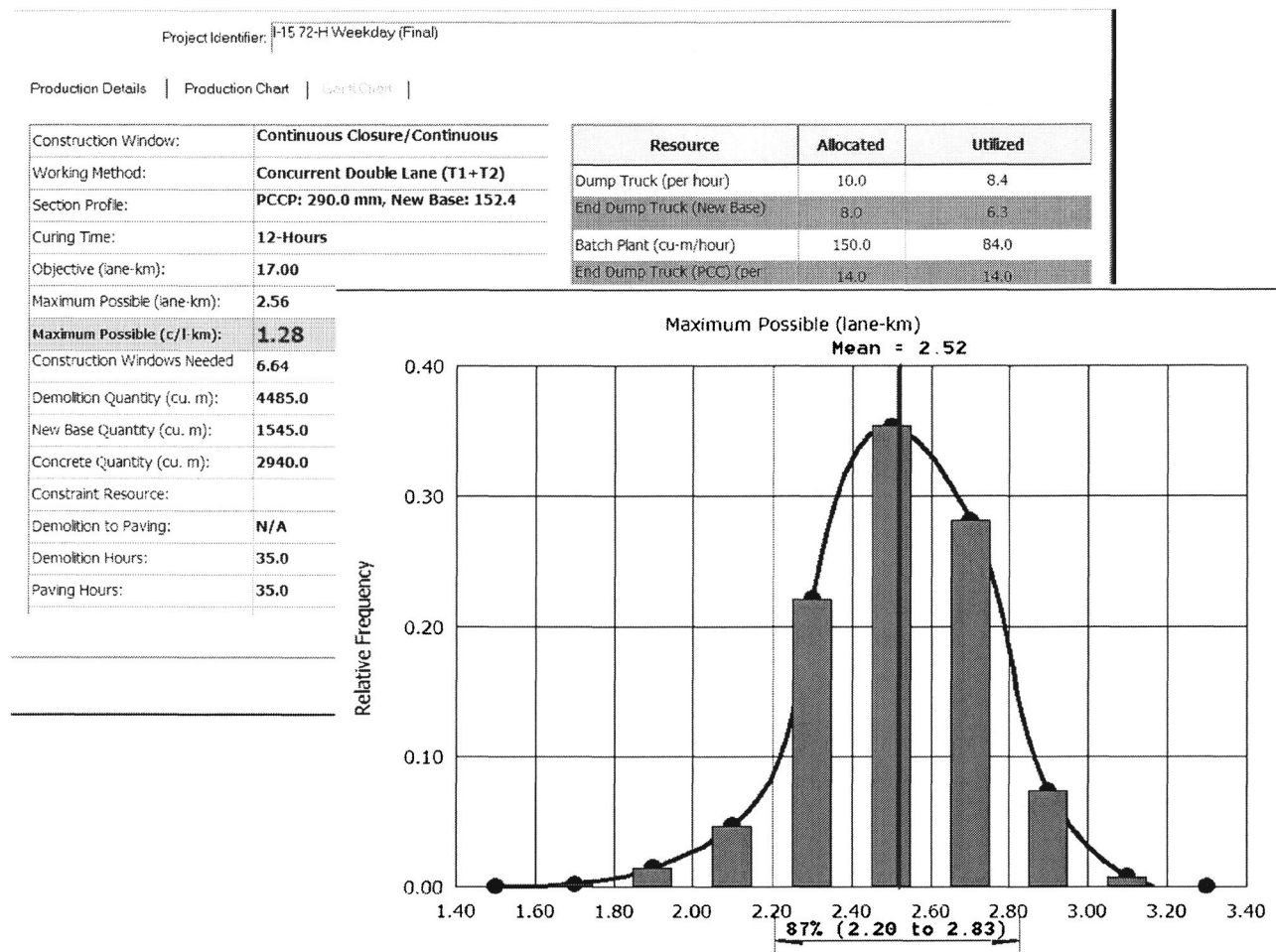


Fig. 5. Output screens for Portland cement concrete deterministic (table) and probabilistic (graph) analysis

tating about two FDAC section (about 0.8 km, basically two overpasses) and 1.3 km of the CSOL section per weekend was overly optimistic. (This optimism may have been encouraged by an incentive provision that offered the contractor \$100,000 per unused weekend closure, cap at \$500,000.) The contractor revised his production plan based on the production levels recommended by the researchers.

The contractor's actual production performance measured in the construction monitoring study by the research team was within about 5% of the CA4PRS production estimates. In addition, the number of demolition hauling trucks (an average of 10 trucks/h) and hot mix asphalt delivery trucks (12 trucks/h on average) predicted by CA4PRS was similar to the contractor's eventual fleet.

Construction Analysis for Pavement Rehabilitation Strategies Integration on I-15 Project

The next case study is on the third Caltrans LLPRS project to rebuild a 4.2 km stretch (total of 17 lane km, two truck lanes in both directions) of Interstate 15, scheduled to begin fall 2004. This highway, near Devore in San Bernardino County, Calif. carries 110,000 ADT on weekends (leisure traffic between Los Angeles, Calif. and Las Vegas, Nev.). A full closure approach ("concurrent double-lane rehabilitation") strategy was selected. The Berkeley research team was involved at the outset to assist in preparing an integrated analysis of pavement materials and de-

sign, construction logistics, and traffic operations. The goal was to determine the most economical reconstruction closure scenario (Lee et al. 2005). The existing pavement structure consisted of 203 mm (8 in.) PCC slabs, 102 mm (4 in.) cement treated base, and 450 mm (18 in.) AB. This old pavement is to be replaced with 290 mm (11.5 in.) of plain, jointed, and doweled concrete slabs utilizing the early strength Type III PCC (so-called "12 h mix") and 152 mm (6 in.) of ACB.

The concept of total cost, integrating closure schedule, road user cost, and construction and traffic handling costs, was used as the evaluation criteria for the most economic closure strategy. The CA4PRS software was used for scheduling analysis as a baseline. The demand-capacity model (*Highway capacity manual*), and macroscopic (*FREQ*) and microscopic (*Paramics*) traffic simulation models were utilized for traffic delay analysis. Caltrans decided to implement eight 72 h weekday closures with round-the-clock operations based on the CA4PRS schedule analysis. The analysis demonstrated that the 72 h closure scenario had 77% less total closure time, 34% less road user cost, and 38% less agency cost when compared with the traditional nighttime closures (Lee et al. 2005).

Conclusions

Construction Analysis for Pavement Rehabilitation Strategies software is structured and designed to predict the maximum

amount (distance) of highway that can be rehabilitated or reconstructed given various parameters, such as pavement materials and design, lane closure tactics, schedule interfaces, and contractor's logistics and resources. The software is a useful constructability analysis tool for transportation agencies and contractors who want to evaluate "what-if" scenarios at each stage of the pavement rehabilitation project: feasibility/planning, design, and construction. It provides a construction schedule baseline for the integration of design, construction, and traffic, all of which are essential for the selection of the most economical pavement rehabilitation strategies. The CA4PRS software can be integrated with traffic analysis tools. When combined with traffic analysis models, CA4PRS can help determine which pavement structures and rehabilitation strategies maximize on-schedule construction production without creating unacceptable traffic delays.

The software has been verified on the Caltrans I-10 Pomona project where concrete long-life pavement was built in a 55 h weekend closure. It has been used to evaluate plans for the Caltrans I-710 Long Beach project where asphalt long-life pavement was built in eight 55 h weekend closures. Further enhancements and upgrades are currently underway so that the enhanced CA4PRS model will cover even more rehabilitation strategies such as a continuous reinforced concrete pavement strategy.

Acknowledgments

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References

- Anderson, A. D., and Russell, J. S. (2001). "Guidelines for warranty, multi-parameter, and best value contracting." *Res. Rep. Series: NCHRP (National Cooperative Highway Research Program) Rep. No. 451*, Transportation Research Board, Washington, D.C.
- Arditi, D., Khisty, J., and Yasamis, F. (1997). "Incentive/disincentive provisions in highway contracts." *J. Constr. Eng. Manage.*, 123(3), 302–307.
- California Department of Transportation (Caltrans). (1998). "Ten-year state highway system rehabilitation plan 1998–99 through 2007–08." (<http://www.dot.ca.gov/hq/transprog/reports/tnyrplan.pdf>) (June 15, 2003).
- Federal Highway Administration (FHWA). (1996). "Public roads." *J. Highway Res. Development*, U.S. Department of Transportation, Washington, D.C., Winter.
- Herbsman, Z. J., and Glagola, C. R. (1998). "Lane rental—Innovative way to reduce road construction time." *J. Constr. Eng. Manage.*, 124(5), 411–417.
- Lee, E. B. (2000). "Constructability and productivity analysis for long life pavement rehabilitation strategies (LLPRS)." PhD dissertation, Univ. of California at Berkeley, Berkeley, Calif.
- Lee, E. B., Harvey, J. T., Ibbs, C. W., and St. Martin, J. (2002a). "Construction productivity analysis for asphalt concrete pavement rehabilitation in urban corridors." *Transportation Research Record 1813*, Transportation Research Board, Washington, D.C., 285–294.
- Lee, E. B., Ibbs, C. W., Roesler, J., and Harvey, J. T. (2000). "Construction productivity and constraints for concrete pavement rehabilitation in urban corridors." *Transportation Research Record 1712*, Transportation Research Board, Washington, D.C., 13–22.
- Lee, E. B., Ibbs, C. W., and Thomas, D. (2005). "Minimizing total cost for urban freeway reconstruction with integrated construction/traffic analysis." *J. Infrastruct. Syst.*, in press.
- Lee, E. B., Lee, H. J., Monismith, C., and Harvey, J. T. (2003). "Fast-track asphalt concrete pavement rehabilitation on I-710 Long Beach (CA) during 55-hour weekend closures." *Preprints of the Transportation Research Board 83rd Annual Meeting* (CD-ROM), Transportation Research Board, National Research Council, Washington, D.C.
- Lee, E. B., Roesler, J. R., Harvey, J. T., and Ibbs, C. W. (2002b). "Case study of urban concrete pavement reconstruction on interstate 10." *J. Constr. Eng. Manage.*, 128(1), 49–56.
- Moder, J., Phillips, C., and Davis, E. (1983). *Project management with CPM, PERT, and precedence diagram*, 3rd Ed., Van Nostrand Reinhold, New York.
- Roesler, J. R., Harvey, J. T., Hung, D., Du Plessis, L., and Bush, D. (1999). "Evaluation of longer-life concrete pavements for California using accelerated pavement testing." *Proc., Accelerated Pavement Testing Int. Conf.*, Reno, Nev.
- "Technology/Business Opportunity: Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS)." (2003). (<http://otl.berkeley.edu/technology/inventiondetail.php/1000916>) (July 6, 2003).
- Timm, D., Voller, V., Lee, E. B., and Harvey, J. T. (2001). "MultiCool: A numerical solution program for multi-layer cooling time of asphalt concrete pavement." *Int. J. Pavement Eng.*, 2, 169–185.
- U.S. Census Bureau. (1994). "Statistical abstracts of the United States 1994: The National Data Book." U.S. Department of Commerce, Washington, D.C.
- U.S. Congressional Budget Office. (1988). "U.S. Congressional Budget Office (CBO) study." (http://www.tc.gc.ca/POL/en/Report/Highway_Benefit-Cost%20Analysis/Chapter5.htm) (December 15, 2003).
- Washington State Department of Transportation. (2002). "Washington State Department of Transportation: I-405 congestion relief & bus rapid transit projects." (<http://www.wsdot.wa.gov/projects/I-405>) (January 2, 2004).
- Wisconsin Department of Transportation (WisDOT). (2002). (<http://www.dot.wisconsin.gov/projects/state/sixyear/hwys.htm>) (June 12, 2003).

Case Study of Urban Concrete Pavement Reconstruction on Interstate 10

Eul-Bum Lee¹; Jeff Roesler²; John T. Harvey³; and C. William Ibbs⁴

Abstract: Many urban concrete pavements in California need to be reconstructed, as they have exceeded their design lives and require frequent maintenance and repair. Information is needed to determine which methodologies for pavement design, materials selection, traffic management, and reconstruction strategies are most suitable to achieve the objectives of California Department of Transportation's (Caltrans) long-life pavement rehabilitation strategies (LLPRS) program. To develop construction productivity information for several construction windows, a case study was performed on a Caltrans concrete rehabilitation demonstration project near Los Angeles on Interstate-10, where 20 lane-km was successfully rebuilt using fast setting hydraulic cement concrete (FSHCC) with one weekend closure for 2.8 lane-km and repeated 7- and 10-h nighttime closures for the remaining distance. The concrete delivery and discharge controlled the overall progress. In terms of the number of slabs replaced per hour, the 55-h weekend closure was 54% faster than the average nighttime closure. An excellent traffic management strategy helped to reduce the volume of traffic during the weekend closure and minimize the traffic delay through the construction zone.

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Introduction

Most urban concrete pavements in California have exceeded their design lives and are in a state of deterioration requiring frequent maintenance and repair (Caltrans 1996). The reconstruction and rehabilitation of these urban concrete pavements is very important to the California Department of Transportation (Caltrans). In 1998, Caltrans launched the long-life pavement rehabilitation strategies (LLPRS) program to rebuild 3,000 lane-km of the state highway network over 10 years. Caltrans expects the concrete pavement to be constructed efficiently with minimal user disruption. When Caltrans launched LLPRS initially, they assumed that fast-track construction of long-life urban concrete pavements would result in a 30-year pavement design, increased safety for users and agency personnel during construction, and reduced user delay costs. To properly assist Caltrans in completing this task, contractors want to be reasonably confident that the project can be

completed within the tight guidelines of fast-track construction with the added long-life pavement features specified by Caltrans.

Very little urban reconstruction of continuous truck lanes has been completed to date in California. Most previous work has consisted of replacement of individual slabs and did not include long-life pavement features such as dowels and tie bars. Caltrans needed to determine which pavement designs, materials, traffic management, and reconstruction strategies were most suitable to help achieve their objectives for long-life pavement and minimal traffic delay.

The main objective of the Univ. of California at Berkeley (UCB) research was to collect information during one weekend (55-h) and repeated nighttime (7- and 10-h) construction closures on Interstate-10 (I-10) in Pomona, Calif. The goal of the case study was to report an overview of the project, traffic management strategies utilized, the contractor's resource and scheduling plans, construction constraints, actual construction productivity and rehabilitation procedures, and a comparison of estimated versus actual productivities (Lee et al. 2000c).

Major Features of Pilot Project

Project Background

I-10 begins in Jacksonville, Florida and extends across the southern United States and terminates in Santa Monica, Calif. The segment running through Southern Calif., commonly called the "San Bernardino Freeway," was built in the early 1960s with a 20-year design life. It has a high concentration of deteriorated concrete pavement. Traffic volumes in this stretch of freeway are as high as 240,000 vehicles—average daily traffic (ADT)—with approximately 9% heavy trucks.

Caltrans selected a 5-km (3.3 mi) stretch from Route 57/210 to Garey Avenue in Pomona (Los Angeles County) as a pilot project for evaluating several of their long-life pavement strategies. Fast setting hydraulic cement concrete (FSHCC), dowels, and tie bars

¹Postdoctoral Researcher, Construction Engineering and Management Program, Dept. of Civil and Environmental Engineering, Univ. of California Berkeley, Berkeley, CA 94720. E-mail: eblee@uclink4.berkeley.edu

²Assistant Professor, Dept. of Civil And Environmental Engineering, Univ. of Illinois at Urbana-Champaign, IL 61801.

³Associate Research Engineer, Pavement Research Center, Institute of Transportation Studies, Univ. of California Berkeley, Richmond, CA 94804.

⁴Professor, Construction Engineering and Management Program, Dept. of Civil and Environmental Engineering, Univ. of California Berkeley, Berkeley, CA 94720.

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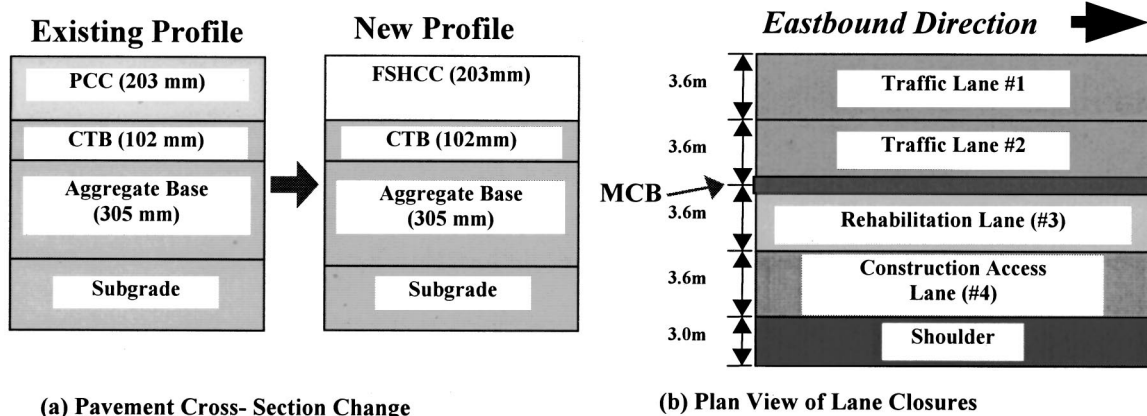


Fig. 1. Cross-sectional change and plan-view of lane closures

were included in the lane rehabilitation strategy. The purpose of the pilot project was to evaluate reconstruction of a truck lane with long-life pavement features and the use of FSHCC to minimize traffic delays during a 55-h weekend closure.

In early 1999, Caltrans awarded a \$15.9 million contract to Morrison Knudsen Corporation (MK) of Highland, Calif. to complete the project. The total volume of FSHCC was estimated at 14,000 m³ to rehabilitate about 20 lane-km of concrete pavement. This 20 lane-km consisted of 5 centerline-km of freeway for eastbound and westbound I-10 in the two truck lanes. The rehabilitation contract began in April 1999 and was completed in February 2000.

Scope of Pavement Rehabilitation

During the 55-h weekend closure, the main rehabilitation task was removal and replacement of the concrete slab without disturbing the cement treated base (CTB). In several locations where the CTB was badly deteriorated, both the slab and CTB were removed and replaced. The existing 230-mm Portland cement concrete (PCC) slab was replaced with the same thickness of FSHCC, as shown in Fig. 1(a). In a previous report to Caltrans on lane rehabilitation (Lee et al. 2000a, 2000b), replacement of the slab and CTB was found to be 50% less productive than replacement of the slab only.

Unique Features of I-10 Project

The I-10 rehabilitation project has several unique features as follows:

- Caltrans decided to use one 55-h weekend closure to check how many lane-km of existing PCC slab could be replaced with new FSHCC instead of repeated nighttime closures and how a weekend closure would impact traffic conditions.
- The contractor used a slab lift-out method for the concrete slab demolition operation. This method was intended to protect the underlying CTB from damage. Caltrans hoped this nonimpact method of demolition would expedite the demolition process and release the slab demolition activity from the potential constraints of the rehabilitation process.
- During the weekend closure, movable concrete barriers (MCBs) were used instead of rubber cones or K-rail between the traffic and rehabilitation lanes.
- Although the traditional low bid concept was used for the I-10 project, incentive and disincentive conditions were applied to

the segment being built during the weekend closure to encourage the contractor to achieve the rehabilitation production objective (Herbsman et al. 1995). An incentive payment would be made to the contractor in the amount of \$600 per lane-meter, for each lane-meter replaced in excess of 2,000 lane-m during the weekend closure (Caltrans 1998). Disincentive would be assessed in the amount of \$250 per lane meter for each lane meter less than 2,000 lane-m. The incentives were capped at \$500,000. A liquidated damage clause was provided in the contract to ensure the closure was open to traffic on Monday morning (\$10,000 liquidated damages per each 10-min period).

7- and 10-Hour Nighttime Closures

The 20 lane-km of existing concrete pavement was to be rehabilitated with repeated nighttime closures except for a 2.8 lane-km stretch to be replaced during the 55-h weekend closure. Work completed in the nighttime closures consisted of replacing individual and/or multiple slabs in a row.

Two types of nighttime closure construction windows were implemented. Ten-hour nighttime closures (10 p.m.–8 a.m.) were implemented for the eastbound freeway and during weekend nights for westbound I-10. Seven-hour nighttime closures (9 p.m.–4 a.m.) were used for the westbound lanes during weekday nights due to the greater traffic volumes heading into downtown Los Angeles during the morning commute. Ten-hour closures covered approximately 64% of the nighttime closures while the 7-h closures covered 36%.

55-Hour Weekend Closure

Caltrans required two of the four lanes to remain open while rehabilitation work was underway. The asphalt concrete shoulder could not be used as a full access lane, because a sound wall limited the shoulder width to 2–3 m.

The 55-h weekend closure began at 10 p.m. on Friday, October 22, 1999, and the rehabilitated lanes were to be opened to traffic again at 5 a.m. on Monday, October 25, 1999. During the weekend closure, 2.8 lane-km were to be removed and replaced in Lane 3 with Lane 4 as the construction access in the eastbound direction as a plan view of the freeway in Fig. 1(b) shows the lane closure tactics utilized.

In the first kilometer of the project, two lanes were assigned for construction access—Lane 4 for main access and the shoulder

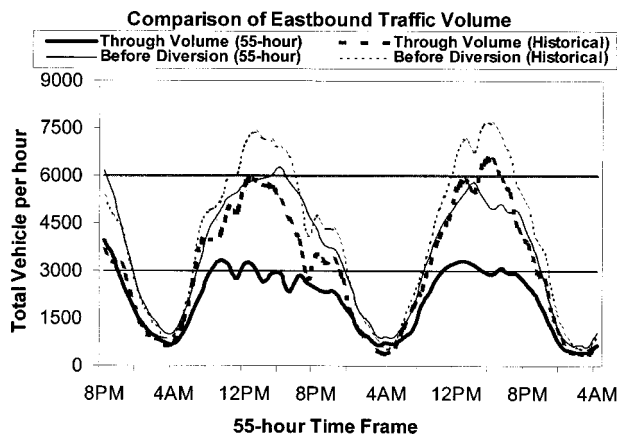


Fig. 2. Traffic levels before versus during construction

as an auxiliary access. For the remaining two-thirds of the project, only Lane 4 was assigned as the construction access because of the narrow shoulder and sound wall. The reduction in the number of access lanes significantly impacted the demolition operation, because trucks entering or exiting the demolition area were blocked by other trucks being loaded.

Traffic Management

Traffic Management Plan

Prior to the 55-h weekend closure, Caltrans and the contractor made a large effort to disseminate information about the I-10 project through media outlets. To control traffic and inform the public of detours during the weekend closure, approximately 100 message and signboards were installed on neighboring freeways, highways, and main arterials near the I-10 corridor.

The goal of the Caltrans traffic plan was to divert as many road users from the I-10 corridor onto alternative routes during the weekend closure. Caltrans advertised the I-10 project plan through sources such as newspapers, television, radio, and flyers for both nighttime and the 55-h weekend closure. Connector route entrances from other freeways as well as two entrance ramps and three exit ramps were closed to the public during the weekend construction but remained open to construction vehicles.

Impact of Weekend Closure to Road Users

With the assistance of Caltrans Traffic Management in District 7, traffic volume data were analyzed to understand the trends of road users during the weekend closure. The traffic data were compared with historical weekend traffic data. Fig. 2 shows that the total traffic volume on two lanes through the construction zone was reduced over historical volumes on four lanes. However, maximum capacity was reached for two lanes (1,500 vehicles/h/lane) during peak hours, similar to typical weekends when capacity was reached for all four lanes. This indicates traffic was still moving at the same level of service as on an average weekend, albeit in only two lanes.

During the weekend closure, the eastbound traffic volume passing through the project site at peak hours (Saturday and Sunday 9 a.m.–9 p.m.) was 30–60% less than peak traffic during typical weekends. The low traffic flow through the construction zone during the day resulted from more road users taking alternate routes than on typical weekends. The total eastbound traffic volume during the weekend closure was 5–35% less than typical weekend peak hours. Off-peak hour vehicles were not concerned

about the weekend lane closures, so diversions during nighttime hours were only 5% less than historical volumes. The overall reduction in traffic volumes on I-10 during the peak hours indicates that road users were well informed. According to Caltrans traffic management, the calculated delay for the project was 19 min based on measured traffic flow data and assuming a maximum flow capacity per lane of 1,500 vehicles/h.

Fast Setting Hydraulic Cement Concrete (FSHCC)

Caltrans selected FSHCC to reduce the concrete curing time for opening to traffic. The cement utilized was Rapid Set, a proprietary cement from CTS Cement Manufacturing Company. The specification required a concrete flexural strength of 2.8 MPa (400 psi) after 4 h and 4.2 MPa (600 psi) within 28 days. The early age strength requirement eliminated PCC from consideration in this project.

FSHCC begins initial set after about 1 h and final set occurs after about 80 min. If the concrete is not discharged shortly after batching, then it begins to build up on the mixer fins in the drum. Traffic congestion on the way to the site, construction zone traffic jams, or a backup in discharging of the preceding mixer trucks may result in rejection of a load, increased buildup in the mixer drum, and/or the temporary loss of the mixer truck from service.

Productivity During 55-Hour Weekend Closure

Contractor's Initial Rehabilitation Plan

The prime contractor for the I-10 project was in charge of drilling holes for tie bars, installing dowel bars, placing the concrete, controlling traffic, and handling the MCB. All other activities, such as demolition, concrete production and delivery, and testing were subcontracted.

The CPM schedule showing the main activities of the rehabilitation with start times, finish times, and duration is summarized in Table 1. The contractor expected that the activities on the critical paths were mobilization, slab removal, FSHCC paving, clean up wash-out areas, apply pavement markers, cure FSHCC, pick up MCB, and open ramps and connectors. The contractor realized that if one activity lagged in production or a breakdown occurred, then the whole rehabilitation process could be delayed, which would jeopardize the targeted completion goal of 2.8 lane-km. For this reason, MK included redundancy in major equipment, including the batch plant, demolition trucks, excavators, paving screeds, and concrete delivery trucks.

In the initial demolition plan, seven end dump trucks were assigned to each demolition team. Three demolition crews could be used at the beginning, as two construction access lanes were initially available (Lane 4 and the shoulder). A 92 m³/h capacity dry mix batch plant from a subcontractor was exclusively used for the project during the weekend closure. A standby batch plant was arranged with the same stock of materials for contingency. Two rotating concrete screeds were mobilized for concrete paving with one screed being used for backup. MK planned to mobilize approximately 35 people for coordination, paving, and traffic control.

Traffic Controls

The first step of the weekend rehabilitation process was traffic control. Traffic control activities were setting up traffic signs,

Table 1. Proposed Schedule versus Actual Schedule for Weekend Closure

Number	Work activity	Proposed Schedule			Actual Schedule		
		Start	Finish	Duration (h)	Start	Finish	Duration (h)
1	Set traffic control	-2.0	-1.0	1.0	-2.0	-1.0	1.0
2	Install moveable concrete barrier	0.0	1.0	1.0	0.0	2.0	2.0
3	Slab demolition	0.0	17.0	17.0	0.5	30.5	30.0
4	Cleaning subbase	0.0	17.0	17.0	1.0	31.0	30.0
5	Drill/tie bar install	0.0	26.0	26.0	2.0	40.0	38.0
6	Dowel baskets	0.0	26.0	26.0	3.0	41.0	38.0
7	Concrete paving	2.0	49.0	47.0	3.5	50.5	47.0
8	Concrete curing	49.0	53.0	4.0	50.5	55.0	4.5
9	Saw cut	4.0	51.0	47.0	6.0	52.5	46.5
10	Pavement marker	45.0	53.0	8.0	45.0	53.0	8.0

Note: Time 0 starts at 10 p.m. on Friday.

closing of entrance/exit ramps and connectors from other routes, and installing MCBs for the lane closure. The contractor began to set up traffic signs 2 h before the lane closure.

The MCB segments were already placed and lined up on the outside shoulder before the weekend closure and only needed to be shifted into place (between Lanes 2 and 3) by a transfer and transport machine. MCB installation for the whole 2.8 lane-km segment was performed within 30 min.

A few days prior to the weekend closure, Caltrans requested a contingency plan from the contractor to open the rehabilitated lane to traffic within 2 h of a notice by the resident engineer. Caltrans issued a letter to the contractor stating the demolition progress could not be more than 20 slabs ahead of the paving operation. The reason for this action was to avoid large delays to the road users traveling through the I-10 Pomona corridor. The contractor would be required to open the rehabilitated lanes to traffic if traffic backup on eastbound I-10 was 30 min longer than that of a normal weekend delay.

Demolition of PCC Slab

Impact and nonimpact demolition methods were used for the project. Most areas required only slab replacement (nonimpact demolition method), while a few areas needed the full-depth slab replacement (impact demolition). For the nonimpact demolition process, slabs were already longitudinally saw cut into three parts during previous nighttime closures.

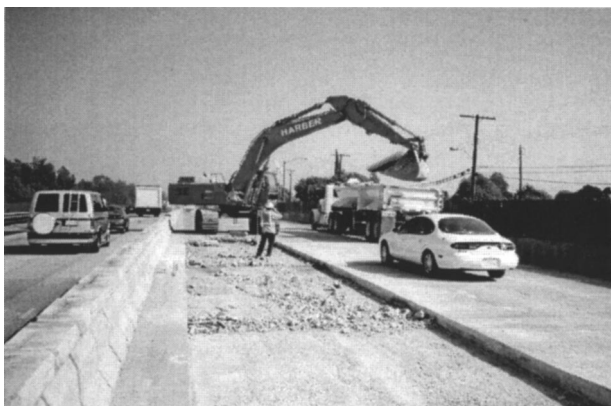


Fig. 3. Nonimpact demolition of existing Portland cement concrete slab

Slab Demolition Process

An excavator with a 1-m³ bucket capacity and seven end dump trucks were initially assigned to each demolition team. With the nonimpact demolition method, the excavator sat in Lane 3 in front of the concrete that it was removing. The excavator then loaded the old concrete into the end dump truck sitting in Lane 4, as shown in Fig. 3. The loading rate of the slabs into the demolition trucks (nonimpact demolition method) was quicker than that of the rubblized slabs (impact demolition method), because the excavator could more easily remove a few large pieces than many smaller pieces. The dumping area was located about 8 km from the job site. Cleaning the base with a front-end loader followed right after the slab demolition.

Where the sound wall was adjacent to the outer shoulder, passage of an empty concrete mixer truck on the way back to the batch plant had top priority. The reason for this was that the concrete paving was the critical activity, and the contractor wanted to avoid buildup in the mixer drums.

As-Built Progress of Slab Demolition

The UCB research team recorded a total of 466 (Table 2) loaded end dump trucks exiting the site to haul out the 615 old concrete

Table 2. Performance of Slab Demolition and Concrete Delivery

Description	Demolition (End dump truck)	Concrete (Mixer truck)
(a) Performance data		
Total number of panels (1 panel = 3.6 m × 4.5 m × 0.23 m)	— ^a	— ^a
Activity duration (h)	30	47
Total number of deliveries	466	440
Average progression (slabs/h)	20	14
Average volume of delivery	10 t (4.2 m ³)	5.2 m ³
Capacity of truck	22 (9.0 m ³)	6.0 m ³
Efficiency of truck	47%	87%
(b) Statistics of demo/delivery trucks		
Average cycle time (min)	5.5	3.5
Average number of trucks per hour	9	10
Average turnaround (min)	64	74
Efficiency of operation (based on average cycle time)	82%	67%

^a615.

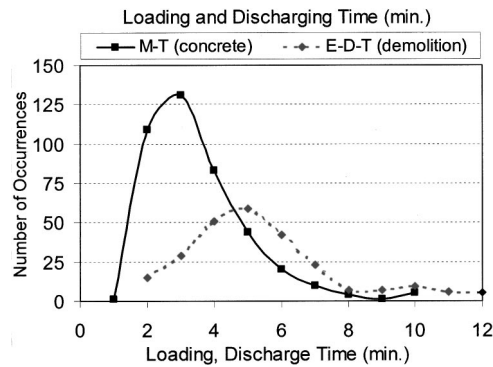


Fig. 4. Demolition loading time and concrete discharging time

slabs. Although the 22-t capacity end dump trucks used for hauling had a 9-m³ capacity (2.7 slabs), each end dump truck carried about 4.3 m³ (1.3 slabs) on average. This meant that only 47% of the total carrying capacity of the end dump truck was utilized, due to the inefficient packing of the large panel pieces.

The average loading time per end dump truck was 5.5 min with a 0.9-min standard deviation, as the distribution of the loading time is shown in Fig. 4. Approximately 9 end dump trucks showed up per hour per crew for demolition with a 2.3 truck standard deviation, as shown in Fig. 5. For every demolition crew, an end dump truck arrived every 7 min. When three crews operated simultaneously, a demolition truck was entering and exiting the construction zone every 2.3 min., and this created construction traffic control problems.

The average turnaround of demolition trucks was measured as 64 min with a 5-min standard deviation, as shown in Fig. 6. Because the turnaround averaged more than 1 h, and the average number of demolition trucks per crew per hour was 9, total 32 demolition trucks had to be mobilized.

Installation of Steel Tie Bars, Bond Breaker, and Dowel Baskets

Tie bars were installed on both sides of Lane 3 during the weekend closure. The tie bars were 16 mm in diameter by 0.75 m in length and were placed at the middle of the slab thickness and spaced 0.75 m apart. The tie bar was inserted into the hole and secured by a fast-setting epoxy. A total of 6,150 holes were drilled in 38 h with two self-propelled gang drill units. The drilling productivity was approximately 80 holes/h/gang drill. This translated into an average progress rate of 72 lane-m/h for the drilling operation. As soon as the tie bar holes were drilled, a 0.15-mm polyethylene sheet was spread on the existing CTB to act as a bond breaker between the CTB and new concrete slab.

Dowel baskets were prefabricated with 10 epoxy coated dowel bars per joint with the steel dowel having a diameter of 38 mm and a length of 0.6 m. A chemical release agent was sprayed on the dowel bars to prevent bonding of the dowel bars to the concrete. Joint locations were chosen to match the existing joints on the adjacent lanes.

Concrete Production and Batch Plant Operation

Dry Mix Batch Plant

A dry mix concrete batch plant (92 m³ capacity) was used for the project instead of central ready mix drum, because buildup on a central drum plant would occur and eventually slow the overall

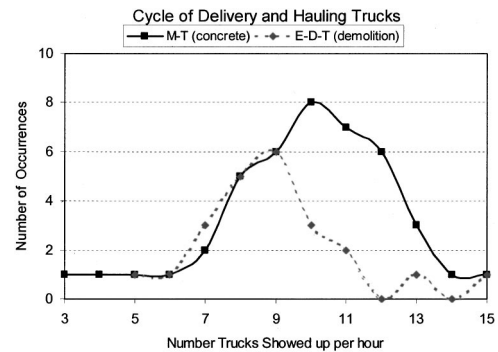


Fig. 5. Number of demolition and concrete trucks per hour

production of FSHCC. On Saturday around 11:30 a.m., the main concrete batch plant suspended its operation because of an electrical breakdown. The standby batch plant supplied only a limited amount of concrete. Approximately 4 h later, the primary batch plant was on-line and concrete delivery began once again. This temporary loss in concrete production ultimately prevented the contractor from finishing the project ahead of schedule.

Buildup of FSHCC in Mixer Trucks

The contractor took special precautions to prevent buildup by washing out every mixer drum with a high-pressure water jet after the truck had discharged its load. On average, the washout process typically took about 15 min per mixer truck out of 74 min of the average turnaround.

At the batch plant, a large scale was used to measure the weight of an empty mixer truck as soon as the mixer arrived back to the plant from its delivery. The amount of concrete buildup in the mix truck drum was obtained by finding the difference between the measured weight of the returning mixer truck and the empty, clean mixer truck weight. During the weekend project, 1 t of FSHCC buildup in the mixer drum was commonly acceptable, and the mixer was left in service until the amount of buildup accrued to 2~4 t. The buildup of FSHCC in the drum also reduced the effective fin length, which caused concern about the mixing effectiveness. Spare mixer trucks were used once trucks were taken out of service for chipping out the hardened concrete from inside the drum. That is why a total of 27 mixer trucks were mobilized but only 20 mixer trucks were in continuous operation.

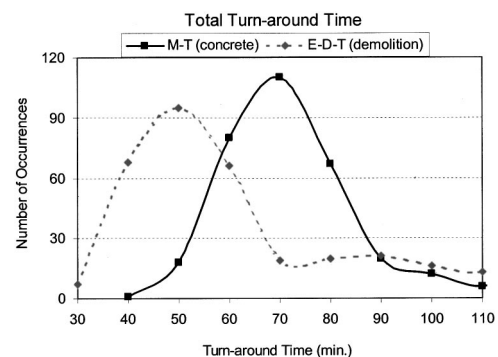


Fig. 6. Total turnaround of demolition and concrete trucks



Fig. 7. Concrete discharge and paving operation

Concrete Delivery

Although the batch plant was regarded as the resource most critical to the rehabilitation process, the concrete mixer trucks proved to be the resource most constraining to the project's production rate. Since agitation was required to prevent the FSHCC from setting up, ready mix trucks (rotating drum) had to be used rather than end dump trucks. Due to the potential for concrete buildup in the drums, only 6-m³ loads were batched into each truck. This load was 20% less than the maximum capacity of the drum (7.5 m³).

At the site, the mixer trucks were positioned on Lane 4 and discharged concrete into Lane 3 in front of the rotating concrete screed, as shown in Fig. 7. The mixer trucks leaving the site were almost always interrupted by the demolition operation in front of the paving operation.

As-Built Progress of Concrete Delivery

The UCB research team recorded concrete mixer truck delivery data throughout the entire 55-h weekend project. For the 55-h weekend, it took 440 concrete delivery trucks to complete 2.8 lane-km (615 slabs of 4.5-m length and 0.23-m thickness). This is equivalent to 1.4 concrete slabs (4.5 m by 3.66 m) per mixer truck delivery. The average efficiency of each mixer truck was 87%. On average, this meant only 5.2 m³ out of each 6-m³ batch from the concrete plant was discharged at the site. The remaining 0.8 m³ of material lost per truck could be attributed to concrete buildup in the mixer truck, material washed out at the site, and trucks that did not discharge at the site due to other paving factors such as screed breakdown.

The average concrete discharge time per mixer truck was measured at 3.5 min with 0.7-min standard deviation, as shown in Fig. 4. This does not include waiting time and time to position the truck in the correct location. The average time for waiting, positioning, and discharging concrete was found to be 6 min.

On average, approximately 10 mixer trucks discharged concrete per hour with a 2.1-truck standard deviation (Fig. 5). The contractor expected the average turnaround of the mixer trucks to be between 45 and 60 min. The actual average turnaround for the mixer trucks was 74 min with a 4-min standard deviation (Fig. 6). Most likely, the contractor underestimated the time it took to wash out the mixer drum, which consisted of waiting in line, removing concrete chutes, and washing out with a high-pressure water jet. The power washing operation was delayed several times due to insufficient water for rinsing. Traffic during the weekend, particularly during the day, also played a role in increasing the turnaround time.

Breakdown of a Mixer Cycle Time (about 70 min.)

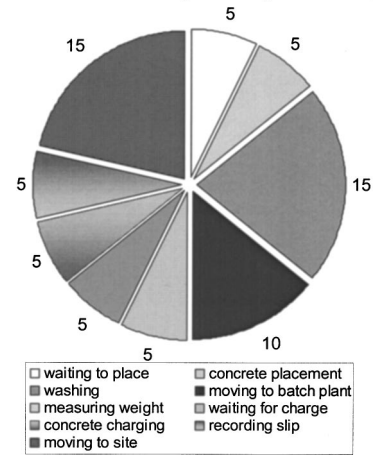


Fig. 8. Components of typical turnaround of mixer truck

Breakdown of Concrete Mixer Truck Turnaround Cycle

Fig. 8 shows that 43% of the mixer truck's operational time is spent driving from the plant to the site and back to the plant. This transit time ends up costing the contractor and agency additional money, because more trucks have to be mobilized in order to meet the concrete volume required at the site.

Fig. 8 shows that the concrete production and placement with FSHCC helped to increase the turnaround for the mixer trucks. If the early strength requirements in the specification were relaxed, then PCC could have been used. Concrete batching could have been 50% faster with PCC, because a central mixing drum could have been used to batch the concrete and charge the trucks. The 5 min in the batch plant area for initial mixing could also have been eliminated, because a central drum plant would complete most or all of the mixing process. The washout process could have been reduced to 5 min or eliminated, because PCC does not build up as rapidly as FSHCC in the mixer drums, and weighing the drum for buildup could have been eliminated with PCC.

Based on these estimates, PCC would have decreased the turnaround for mixer trucks by about 30%. This means that an FSHCC operation probably requires 30% more mixer trucks to supply the same volume of concrete at the jobsite. This comparison suggests that there are ideal construction windows where FSHCC is the most efficient material to use for rehabilitation such as 7-h and 10-h nighttime closures, while longer construction windows make PCC the preferred material.

Concrete Paving and Finish Work

The FSHCC had a high slump, because it was being placed by hand. Finishing and texturing were completed by two laborers who floated, trowelled, and broomed the pavement surface behind the concrete screed. Curing compound was sprayed on the surface immediately after finishing and texturing. Approximately 2 h after the concrete was finished, a 44-mm deep saw cut was made for each transverse joint using a single saw team. The condition of the finished concrete pavement surface was rough, but the contractor had planned on diamond grinding the surface later, as part of the contract with Caltrans.

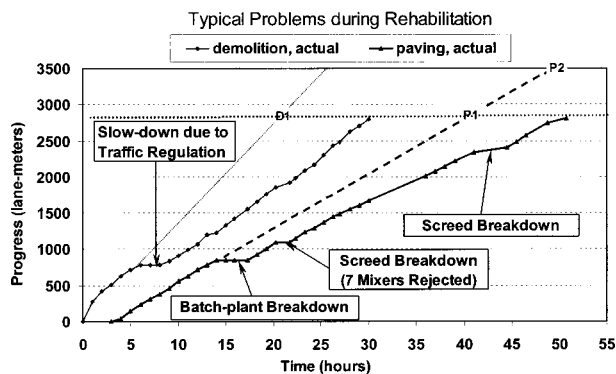


Fig. 9. Overall rehabilitation progress for demolition and concrete paving

Comparison of Actual Progress with Proposed Progress

Table 1 presents a comparison between the planned CPM and the as-built CPM schedule. Most of the activities progressed as planned, except for the existing slab demolition activity, which required an additional 13 h. One cause of the demolition slow down was the constraint placed on the contractor to open the construction site back to traffic within 2 h. During day 2 of the project, the narrow shoulder along with the presence of an adjacent soundwall caused access problems for the demolition operation, and thus it could not efficiently complete the task in the initial specified time.

The actual duration of the paving operation was the same as the contractor's original schedule. Four of the total paving operation hours were due to the batch plant breakdown, which meant the contractor actually had fewer net paving hours than originally planned.

Overall Progress of Rehabilitation

Fig. 9 shows that the planned and actual demolition rates were initially similar, but changed 5 h from the start, due to the reduction in the number of demolition crews to comply with Caltrans' contingency plan for opening the site back to traffic.

As shown in Fig. 9, the paving operation experienced several delays. The batch plant broke down for 4 h, and the paving screed broke down in two instances, temporarily suspending the operation. However, the contractor still achieved the rehabilitation goal

within the 55-h weekend. Without the breakdown in the batch plant and the screeds, the contractor could have finished 6 h earlier.

The slope of the paving progress in Fig. 9 shows a gradual slowdown at the end of the operation relative to the initial production rate due to construction fatigue of the paving crew (for example, an average paving production of 77 m/h from hours 0 to 4, while 61 m/h of paving production from hours 24 to 41). The paving crew was observed to work continuously without major shifts or rests during the weekend project. Fig. 9 also indicates that paving productivity was the same for both daytime and nighttime operations.

Discussion of Demolition and Paving Productivity

Further conclusions can be drawn from Fig. 9:

- Based on the initial progress rate shown in Fig. 9, the fastest the concrete slab demolition could have been completed was 22 h based on a maximum of three crews as marked "D1" in Fig. 9. This would have saved the contractor 8 h of labor from the actual duration of 30 h.
- The paving operation could have been completed by hour 42 instead of hour 51 as marked by "P1" in Fig. 9, based in the initial paving rate. If paving could have progressed at this rate, then the rehabilitation project would have been completed in 46 h rather than 55 h.
- The maximum amount of concrete paved, based on the contractor's process, paving rate, and resources, would have been 3.5 lane-km, if the contractor had continued paving at full capacity without any work stoppages during the 55-h construction window. This ideal production of 3.5 lane-km can be read as point "P2" in Fig. 9. Based on the maximum allowable amount of paving, the efficiency of the contractor's paving operation can be calculated as 80% (2.8 lane-km/3.5 lane-km).

Production Comparison of Weekend Closure with Nighttime Closures

A detailed comparison of the slab replacement productivity for the two nighttime closures (7 and 10 h) and the 55-h weekend closure is summarized in Table 3 (Lee et al. 2000c). The definition of productivity used in Table 3 is based on the average number of slabs replaced per hour without consideration of the number of resources involved in the rehabilitation process.

Table 3. Comparison of Productivity for Different Construction Windows

	Nighttime Closure		Weekend Closure
	7-h closure	10-h closure	55-h closure
Closed time	9 p.m.–4 a.m.	10 p.m.–8 a.m.	10 p.m. (Friday)–5 a.m. (Monday)
Net working hours (concrete pouring)	2 h	5 h	43 h
Auxiliary hours (mobilization/curing/demobilization)	5 h	5 h	8 h
Typical production (slabs per closure) ^a	15	50	615
Productivity (slabs per hour)	7.5	10	14
Major resources	7 dump trucks; 4 mixer trucks	7 dump trucks; 8 mixer trucks	21 dump trucks; 12 mixer trucks

^aTypical panel size is 0.2-m thick \times 3.6-m width \times 4.5-m length.

Table 3 shows that the additional 3 h of work in the 10-h closure versus 7-h closure greatly enhanced the productivity of the nightly operation (50 slabs versus 15 slabs replaced). The 10-h nighttime closures were 33% more productive per hour than the 7-h closures because approximately 5 h were available for the actual slab replacement work versus 2 h for the 7-h closures. Five hours are needed in both types of nighttime closure for mobilization, demobilization, and curing. This can be further extrapolated to 55-h weekend closures, where mobilization, demobilization, and curing times became a smaller percentage of the total project length, and thus more productivity was achieved. In terms of the number of slabs replaced per hour, the 55-h weekend closure was 54% more productive than the average nighttime closure.

The amount of the rehabilitation work done over the 55-h extended closure would have normally taken approximately 16 days of nighttime lane closures to complete. From the road user's point view, when the total duration of lane closures for 16 days of nighttime closure is compared to one weekend closure, the duration of the 55-h weekend closure is only 38% of the 16 nighttime closure duration.

For nighttime closures, a 4-h opening strength material is required to achieve the proper concrete strength to open the lane back to traffic in a relatively short construction window. This is one reason for the use of FSHCC in nighttime closures. The benefits of FSHCC for a 55-h weekend closure may not outweigh its costs, and it may not be the most efficient material to use for weekend closures.

Case Study Conclusions

A 2.8 lane-km rehabilitation project on the I-10 near Los Angeles using fast setting hydraulic cement concrete (FSHCC) was successfully completed during a 55-h weekend closure. The rehabilitation project consisted of replacing the 230-mm concrete slab with new concrete, dowels, and tie bars. The contractor used a concurrent working method in which demolition and concrete paving occurred simultaneously and only a single lane was removed and replaced. Under the Caltrans incentives/disincentives clause in the contract, the contractor qualified for a \$500,000 bonus payment for completion of the 2.8 lane-km stretch of rehabilitation over the weekend closure.

Slab demolition took 76% longer than the contractor's proposed schedule, but it did not slow the overall progress of the rehabilitation. The packing efficiency of the end dump trucks for demolition was found to be 47%.

Concrete delivery and discharge at the site were found to be the constraining factors. The average efficiency of the concrete delivery trucks was found to be 87%. FSHCC played a role in reducing the overall efficiency of the concrete mixer truck deliveries, primarily due to material buildup in the mixer drums.

During the weekend closure, an average of 14 slabs were paved per hour. The weekend closure was 54% more productive

in terms of slabs replaced per hour compared with previous 7-h and 10-h nighttime closures by the contractor. The amount of the rehabilitation work performed over the 55-h extended closure would have normally taken 16.4 days of nighttime closures.

The estimated comparison of the cycle time of mixer trucks and batch plant for FSHCC and PCC suggests that the ideal construction windows for FSHCC are 7-h and 10-h nighttime closures, while PCC is the preferred material for longer construction windows.

During peak hours (Saturday and Sunday 9 a.m.–9 p.m.), traffic volumes through the construction were reduced by 30–60% compared with the peak traffic during typical weekends. Only two lanes were available instead of four, and traffic operated at capacity in those two lanes during peak hours. The percentage of traffic diverting to other routes doubled during the 55-h weekend closure during the daylight hours, but was only approximately 5% more than normal during the nighttime hours.

Acknowledgments

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References

- California Department of Transportation (Caltrans). (1996). *1995 state of the pavement*, Caltrans Maintenance Program, Pavement Management Information Branch, Sacramento, Calif.
- California Department of Transportation (Caltrans). (1998). "Notice to contractors and special provisions for construction on state highway in Los Angeles County in Pomona from Route 210/57/10 interchange to Garey Avenue undercrossing." *Contract No. 07-181304*, Sacramento, Calif.
- Herbsman, Z., Chen, W. T., and Epstein, W. C. (1995). "Time is money: Innovative contracting methods in highway construction." *J. Constr. Eng. Manage.*, 121(3), 273–281.
- Lee, E. B., Roesler, J. R., Harvey, J. T., and Ibbs, C. W. (2000c). "Case study of urban concrete pavement reconstruction and traffic management for the I-10 (Pomona, Calif.) project." *Research Reports and Findings No: DTFH61-99-X-00008*, Innovative Pavement Research Foundation, Falls Church, Va.
- Lee, E. B., Ibbs, C. W., Harvey, J. T., and Roesler, J. R. (2000a). "Constructability and productivity analysis for long life concrete pavement rehabilitation Strategies." *Final Rep. FHWA/CA/OR-2000/01*, Pavement Research Center, Univ. of California, Berkeley, Calif.
- Lee, E. B., Ibbs, C. W., Roesler, J. R., and Harvey, J. T. (2000b). "Construction productivity and constraints for concrete pavement rehabilitation in urban corridors." *Transportation Research Record No. 1712*, Transportation Research Board, Washington, D.C., 13–22.

Fast-Track Urban Freeway Rehabilitation with 55-H Weekend Closures: I-710 Long Beach Case Study

Eul-Bum Lee¹; Hojung Lee²; and John T. Harvey³

Abstract: As an asphalt concrete demonstration project implemented under the California Department of Transportation's Long-Life Pavement Rehabilitation Strategies program, a 4.4 km stretch of Interstate-710 (I-710) in Long Beach was successfully rehabilitated during eight repeated 55-h extended weekend closures using around-the-clock construction operations and counterflow traffic. This case study documented the accelerated rehabilitation process, assessed traffic impacts, and compared collected productivity data. Compared to the productivity rates of traditional nighttime closures, the 55-h weekend closures effectively reduced the construction duration and the overall traffic inconvenience. Noticeable improvement ("learning-curve effect") in the contractor's production rates was observed as the weekend closures were repeated. As a result of a significant (38%) traffic demand reduction through the work zone, the traffic impact of construction closures was tolerable to the extent that traffic was in free-flow condition throughout the highway network. This case study will be useful for transportation agencies and contractors in developing integrated construction and traffic management plans for urban freeway rehabilitation projects to maximize pavement life expectancy and construction productivity while minimizing agency and road user costs.

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CE Database subject headings: Asphalt pavements; Construction management; Fast track construction; Highway construction; Monitoring; Productivity; Reconstruction; Rehabilitation.

Introduction

Need for Highway Rehabilitation in California

Rehabilitation of urban freeways is a critical issue confronting the California Department of Transportation (Caltrans) as more than 90% of the 78,000 lane/km of the state highway system have exceeded their original 20 year design lives and show extensive signs of distress requiring immediate rehabilitation and reconstruction (Caltrans 1998). In response to ever-increasing maintenance and rehabilitation backlogs and continual shrinkage in the available budget, Caltrans decided to introduce long-life pavements for rehabilitation of deteriorated urban freeways. It was expected that the savings over the life of the pavements, in terms of reduced maintenance and rehabilitation requirements,

decreased numbers of traffic delays, and reductions in accident exposures for freeway users, would offset the initial premium cost of long-life pavements.

In 1998, Caltrans launched the Long-life Pavement Rehabilitation Strategies (LLPRS) program with an estimated \$1 billion investment plan for rebuilding approximately 2,800 lane/km of severely distressed urban freeways over the next 10 years (Caltrans 1998). Most of candidate segments were concrete paved interstates in the urban highway networks of the Los Angeles (80%) and the San Francisco Bay, Calif. (15%) areas. For these candidate segments under high traffic volumes, Caltrans' goal was to provide pavements with design lives of 30 plus years while: (1) minimizing traffic disruptions and road user cost; (2) providing a safe work environment for construction workers and freeway users; and (3) reducing impacts on the neighboring business community and the environment.

Since the launch of the LLPRS program, Caltrans has completed two demonstration projects utilizing 55-h weekend closures (from 10 p.m. Friday to 5 a.m. Monday) with the around-the-clock construction operations. The first project was on Interstate I-10 (I-10) near the city of Pomona where a 2.8 lane/km segment of a deteriorated concrete truck lane was rebuilt with fast-setting hydraulic cement concrete in one 55-h weekend closure in the fall of 1999 (Lee et al. 2002). The second was the I-710 Long Beach project, as introduced in this paper, where a 4.4 km stretch of badly damaged concrete pavement was rehabilitated with long-life asphalt concrete (AC) pavements during eight 55-h weekend closures in the spring of 2003.

Study Objectives and Methodology

This case study summarized the state-of-practice strategies used to accelerate construction and minimize traffic impacts on the

¹Research Engineer, Institute of Transportation Studies, Univ. of California at Berkeley, 1353 S. 46th St., Bldg. 452 (PRC), Richmond, CA 94804 (corresponding author). E-mail: eblee@berkeley.edu

²Graduate Student Researcher, Dept. of Civil and Environmental Engineering, Univ. of California at Berkeley, 215 McLaughlin Hall, Berkeley, CA 94720. E-mail: hoj2@berkeley.edu

³Associate Professor, Dept. of Civil and Environmental Engineering, Univ. of California at Davis, 3139 Engineering III, 1 Shields Ave., Davis, CA 95616. E-mail: jtharvey@ucdavis.edu

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I-710 Long Beach project, fast-track urban freeway rehabilitation in California. The construction study monitored the as-built process and progress over three of eight 55-h weekend closures, paying particular attention to the hourly progress of major operations in conjunction with truck cycle times allowed by repeated weekend closures.

Beginning with construction data from the first LLPRS demonstration on I-10 Pomona, Calif., Caltrans has been developing a contractor's production rate database that can be used for future LLPRS construction management planning documentation. The collected construction progress data is stored in the reference database of the construction analysis for pavement rehabilitation strategies (CA4PRS) software, which was designed to estimate the minimum duration of LLPRS projects under a given set of project constraints, including schedule interfaces, pavement design, construction logistics, and traffic operations (Lee and Ibbs 2005).

The study also evaluated the contractor's "learning-curve effect" in achieving the project's monetary incentive compensation goal, comparing production rate changes, as the weekend closures were repeated, on similar rehabilitation processes in accelerated construction under schedule pressure. Similarly, the construction case study quantitatively compared production rates from the perspective of different operation variables, such as delivery methods, surface conditions, and pavement designs.

A traffic monitoring study was conducted simultaneously to evaluate the traffic delay impact of the weekend closures on a highway network under high traffic volumes. The traffic impact was assessed and quantified with the measurement of changes in traffic statistics (volume, speed, and travel time) by comparing "before-construction" (historical) and "during-construction" weekends.

This study, based on collected construction data, traffic data, and lessons learned, was designed to help Caltrans engineers and other transportation agencies assess and refine construction and traffic management plans for future high volume urban freeway rehabilitation to maximize construction productivity and minimize traffic delay. The study will be useful for contractors in developing accelerated construction staging plans that account for the effects of the learning curve across repeated, short, intense work periods.

Unique Features of I-710 Project

Project Overview

The I-710 Long Beach project was to rebuild, with long-life AC, about 4.4 centerline km (total of 26.3 lane/km) of the six-lane concrete segment (including median and outside shoulders) of I-710 near the Port of Long Beach. The main rehabilitation work was completed in eight 55-h weekend closures. First opened to the public in the early 1950s, the freeway segment is a heavily congested commuter/truck route, carrying an average daily traffic (ADT) of more than 164,000 vehicles during weekdays with heavy trucks accounting for close to 13% of the total traffic (Caltrans 2003). Having been in service for more than 50 years without a major rehabilitation, and subjected to the heavy axle loads by the high percentage of truck traffic, the existing concrete pavements were severely deteriorated with excessive cracking and faulting contributing to poor ride quality.

Two rehabilitation strategies were implemented for the existing pavements consisting of 203 mm Portland cement concrete (PCC) slabs on top of cement treated base (CTB) and aggregate base (AB) layers. For most of the segment (2.8 km total length), the PCC slabs were cracked, seated, and overlaid (CSOL) with AC. Under four overpass structures (1.6 km total length), where minimum clearance requirements did not allow an AC overlay, full-depth asphalt concrete (FDAC) reconstruction replaced the old PCC slab, CTB, and AB, with additional excavation to comply with the Federal Highway Administration interstate bridge clearance requirements.

In the project's special provisions (SP), a total of ten consecutive 55-h weekend closures were allowed for the main rehabilitation work of CSOL AC overlay and FDAC reconstruction operations. An unlimited number of 7-h nighttime closures (from 9 p.m. to 4 a.m.) were permitted for the preparatory works, including widening and upgrading of median and outside shoulders and replacement of the old median metal guardrails with new concrete barriers. The placement of the final surfacing layer (25 mm rubberized AC layer) was carried out during the subsequent 7 h nighttime closures after completion of the weekend closures for the main rehabilitation work.

The SP included a monetary incentive/disincentive clause to encourage earlier project completion and on time reopening of the freeway. The contractor was entitled to an incentive amount of \$100,000/weekend closure if the main rehabilitation work was completed in fewer than ten weekend closures. Conversely, the contractor was subjected to a disincentive penalty of \$100,000 if more than ten weekends were required for the designated work. The total amount of incentive or disincentive was limited to \$500,000.

The preparatory works in the median started in April 2001 with an initial total contract amount of \$16.7 million. A number of unexpected problems, such as hazardous asbestos in the median, roadway alignment discrepancies between the plan and actual surveys, and delay in finalizing AC mix binder contents, were encountered, but these problems did not cause any substantial traffic delay impact. They did push the start of weekend closures back about 1 year to March 2003. Encouraged by the incentive award, the contractor was however able to complete all the main rehabilitation work by the eighth weekend closure in June 2003, two weekends ahead of the initial Caltrans plan. The final construction cost, including additional compensations for contract change orders to address the above-mentioned adverse issues, increased to about \$20 million at the end.

Long-Life Pavement Design

Fig. 1 shows the 230 mm AC overlay design specified for the CSOL sections. It includes four AC layers containing either AR-8000 (PG64-16) or PBA-6a (PG64-40) binders on top of cracked and seated PCC pavement. The use of both binders (i.e., conventional AR-8000 with high stiffness and polymer modified PBA-6a with larger rut resistance) was intended to reduce the pavement section thickness while ensuring adequate fatigue and rutting performances. The pavement reinforcing fabric between the first two AC lifts was to serve as a stress-absorbing interlayer to slow down reflection cracking from the bottom. The rubberized AC open-graded friction course (OGFC) was intended to serve as a sacrificial top layer for top-down cracking and to reduce tire splash and spray, hydroplaning potential, and tire noise

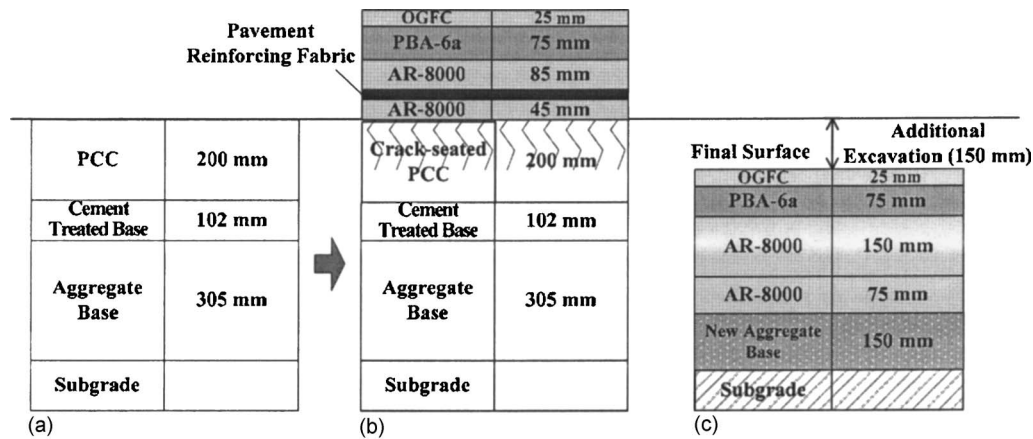


Fig. 1. Typical pavement cross-section changes: (a) existing pavement; (b) CSOL [crack, seat, and AC overlay (230 mm)]; and (c) FDAC (full-depth AC replacement (325 mm))

as well. It was intended that this OGFC would be periodically (about every 10–12 years) removed and replaced during the service life of the pavement.

As also shown in Fig. 1, the pavement design for the FDAC sections consists of 325 mm AC layers on top of 150 mm of new AB layer. The FDAC pavement design incorporated the same AC materials as specified in the CSOL pavement design, except for the first AR-8000 rich bottom layer, to provide additional stiffness and fatigue resistance.

The asphalt mix designs for the project were obtained using mix design/analysis technology developed through the Strategic Highway Research Program (St. Martin et al. 2001). The CSOL and FDAC pavement sections were designed using mechanistic-empirical design methodologies to accommodate 200 million equivalent single axle loads for a life of 30 plus years. Prior to the start of the project, the rutting resistance of PBA-6a mix designs was verified through heavy vehicle simulator testing (Deacon et al. 2002).

55-h Extended Weekend Closure

I-710 Long Beach was Caltrans' first major LLPRS urban freeway rehabilitation project to incorporate a series of 55-h weekend closures. The 55-h weekend closure alternative was implemented for this project because peak hourly traffic volumes through the I-710 Long Beach area are significantly lower on weekends than on weekdays: 4,300 versus 5,400 vehicles/h. It was anticipated that the weekend schedule would produce far fewer traffic delays.

The decision was also based upon experience with the previous I-10 Pomona LLPRS project. There hourly rehabilitation progress during a 55-h weekend closure, utilizing around-the-clock construction operations, was observed to be nearly 40% greater than the hourly progress achieved using 7- or 10-h nighttime closures (Lee et al. 2002). The large difference in the rates of progress was mainly due to the portion of time nighttime closure crews spent on mobilization/demobilization and traffic control, or "nonworking" activities. This suggested that nighttime closures in the urban highway network would result in longer overall closure time, therefore higher construction and traffic handling costs, and potentially greater traffic delay costs for freeway users.

Of key importance to the goals of the LLPRS program, 55-h weekend closures generally allow a focus on creating long-life pavements that 7- and 10-h nighttime closures do not. In the past, rehabilitation of urban freeways in California was done during

7- or 10-h nighttime closures. However, the types of pavement structures that can be constructed during short-term nighttime closures are limited to types with service lives of no more than 10–15 years, far short of the 30 plus year design lives envisioned for LLPRS projects. The 55-h closures were also expected to ensure better surface conditions, while pavement structures designed for nighttime closures are generally expected to have relatively inferior surface condition and ride quality, in part due to the limitations on construction quality control imposed by tight time constraints. Finally, the estimated volume of materials to be hauled away and brought into the site for LLPRS projects was too large to be handled efficiently within such a short time frame.

Traffic Control and Management

In order to maintain traffic flow while ensuring a safe environment for both construction workers and freeway users, Caltrans applied "counterflow traffic," wherein both directions of traffic were temporarily aligned to the traffic roadbed on the other side of the construction roadbed through predetermined openings in the median, called "traffic crossovers." The outside shoulder on the traffic roadbed was temporarily converted to a main traffic lane to provide two traffic lanes in each direction and movable concrete barriers (MCBs) were installed as a safety divider between the two directions of traffic (Fig. 2). At the beginning and end of each weekend closure, both directions of the freeway were completely closed for about 6–8 h for installation/removal of the MCB and pavement striping while traffic was being detoured to the local arterial roads.

During the project's design stage, a microscopic simulation study was conducted to estimate the impact of weekend closures on the traffic network (Lee et al. 2004). The simulation estimated that with a traffic handling capacity through the construction work zone (CWZ) of 3,000 vehicles/h (with two lanes open for each direction), well below the weekend peak demand of 4,300 vehicles/h, weekend peak hour delays of as much as 220 min would likely occur. In order to encourage diversion to arterial roads and neighboring freeways and induce a reduction in traffic demand through "no-shows," several methods of informing the freeway users of potential delays and alternate routes were included in the Caltrans' traffic management plan (TMP). These included public awareness campaigns, portable and permanent changeable message signs (PCMSs), and highway advisory radio



Fig. 2. Around-the-clock construction operations and counterflow traffic with MCB

messages. In total, 230 roadway guide signs and 26 PCMSs were installed on the traffic network during each weekend closure.

Accelerated Rehabilitation Construction

Fig. 3 shows the contractor's critical path method (CPM) schedule during a typical 55-h weekend closure. Because of extreme time, space, and resource constraints, the CSOL overlay and FDAC replacement operations were performed around the clock with activities being planned concurrently. Considerable amounts of schedule float were assigned to the FDAC replacement activities against the possible adverse subgrade condition. The following are the major rehabilitation activities performed during the typical weekend closure:

1. Traffic closure:
 - Set up CWZ signs and close both directions of the freeway temporarily;
 - Set up MCB and place temporary striping and markers on the traffic roadbed; and
 - Open counterflow traffic through the traffic roadbed.
2. CSOL rehabilitation:
 - Crack and seat existing PCC pavement;
 - Place 45 mm of AR-8000 leveling course;

- Install pavement reinforcing fabric; and
- Place 85 mm of AR-8000 and 75 mm of PBA-6a.

3. FDAC reconstruction:
 - Fracture (rubblize) and remove existing PCC pavement;
 - Excavate CTB and AB layers and cut subgrade;
 - Place 150 mm of new AB layer; and
 - Place 75 mm of AR-8000 rich bottom, 150 mm of AR-8000, and 75 mm of PBA-6a.
4. Traffic opening:
 - Place striping and markers on new pavement;
 - Close both directions of the freeway again;
 - Relocate MCB to the median and restore the original striping and markers; and
 - Remove CWZ signs and reopen both directions of the freeway.

During each weekend closure, the paving crew started with the CSOL AC overlay operation, then proceeded to the FDAC AC paving once the compaction on new AB was completed. The median and outside shoulder were completely overlaid or replaced with AC along with three main traffic lanes, in four strips (pulls), each approximately 4.3 m in width. An alternating strip paving sequence between the lanes was used to avoid potential paving stoppages due to AC cooling time required.

Contractor Quality Control

The project's SP included a contractor quality control requirement that held the contractor responsible for the final AC pavement quality. The contractor was required to submit shear and fatigue test results on his AC materials for mix design approval and field performance test results on three AC quality characteristics: (1) asphalt content; (2) gradation; and (3) percent of maximum theoretical density. Payment to the contractor for AC was adjusted based upon a combination of pay factors determined for the three quality characteristics with weighting factors of 0.3 for asphalt content, 0.3 for gradation, and 0.4 for percent of maximum theoretical density. The maximum achievable compensation adjustment factor was 1.05 with a minimum acceptable factor of 0.90. The inclusion of the pay factor clause effectively encouraged quality awareness and quality workmanship on the part of the contractor.

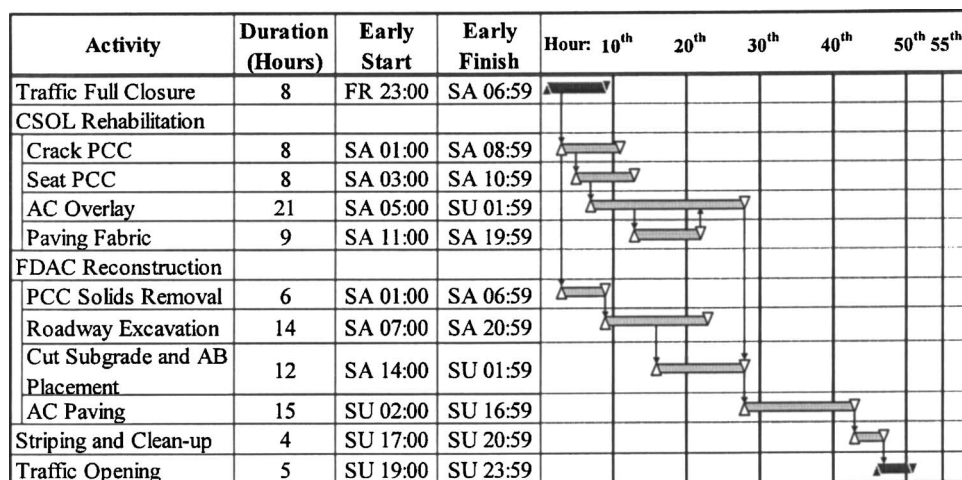


Fig. 3. Typical CPM schedule for 55-h extended weekend closure (second weekend closure)

Table 1. Production Summary of 55-h Extended Weekend Closures

Periods	Activities	Unit	Estimated quantity	Duration (h)	Average trucks per hour	Average hourly production rate
First weekend closure	CSOL AC overlay	t	7,595	22.2	14.9	341.6
	FDAC demolition/excavation	m ³	3,342	20.8	18.4	161.1
	FDAC AC paving	t	4,204	18.5	10.1	227.9
Second weekend closure	CSOL AC overlay	t	4,846	12.4	17.8	393.0
	FDAC demolition/excavation	m ³	4,939	24.0	25.6	205.8
	FDAC AB placement	m ³	1,059	10.1	14.5	104.5
	FDAC AC paving	t	6,208	24.2	11.5	256.6
Seventh weekend closure	CSOL AC overlay	t	7,089	20.0	15.8	355.3
	FDAC demolition/excavation	m ³	3,200	13.9	30.5	231.0
	FDAC AB placement	m ³	1,100	7.9	15.0	139.5
	FDAC AC paving	t	3,877	12.3	13.9	314.4

Productivity Monitoring

Monitoring Method

The contractor started the first weekend closure on March 28–31, 2003 and completed all the designated main rehabilitation work by the eighth weekend closure on June 20–23, 2003, excluding the weekend of the Long Beach Grand Prix, Easter, and Memorial Day weekends, and two weekends with bad weather. The research team monitored the contractor's as-built process and progress during the first, second, and seventh weekend closures as the planned work scope and resource configurations were relatively similar to each other during these periods.

Initially, a global positioning system (GPS) was to be used for tracking rehabilitation progress and cycle times for hauling and delivery trucks. Tracking measurements were eventually done manually when the accuracy of available GPS devices was deemed to be inadequate. During each weekend closure, 10–12 monitoring staffs were stationed around the CWZ for recording the planned and actual activity durations, material quantities, truck cycle times, and hourly production rates of the major rehabilitation activities. This was more comprehensive monitoring than that which was done for the study on the I-10 Pomona reconstruction (Lee et al. 2002). The contractor's station benchmarks, placed along the outside shoulders, were referenced to keep track of the hourly activity progress, and all the trucks mobilized for the major activities were individually marked with reflective magnetic placards for recording hourly truck discharges and turnaround cycles. Table 1 summarizes the contractor's as-built progress of the major rehabilitation activities over the three monitored weekend closures.

Utilized Resources

During each 55-h extended weekend closure, the contractor maintained two alternating shifts of about 40 site personnel for the around-the-clock rehabilitation operations. Each shift consisted of one AC paving crew, two demolition/excavation crews, one pavement reinforcing fabric placement crew, and one PCC cracking/sealing crew. Major demolition equipment included two excavators, three front loaders, two motor graders, one milling machine, four mechanical breakers (also known as "stompers") for rubblizing PCC slabs, and two guillotine breakers for PCC slab cracking. Paving equipment included two self-propelled asphalt pavers (one with a hopper only and the other with a hopper and a windrow elevator), two pneumatic-tired rollers, three vibratory steel rollers,

one water tank truck and one tack coating truck. Additional backup equipment was on standby near the work site with stockpile materials at the backup batch plant. On average, a total of 35 demolition hauling and 42 hot mix asphalt (HMA) delivery trucks were mobilized at each weekend closure.

Demolition and Base Placement Productivities

Two concurrently working demolition/excavation crews removed an average of 3,827 m³ of PCC solids and road base materials in 19.6 h during each weekend closure, similar to the contractor's planned 19.3 h. The average hourly truck loads hauled away by the two crews was 24.2 with about 5 min loading time per truck. The dumping yard was located approximately 4 km from the project site near the Port of Long Beach and the average turnaround time of the hauling trucks was 42 min.

The PCC removal (demolition) was completed as scheduled, but the roadway excavation (including subgrade cutting and compaction) took longer than planned, especially during the first weekend closure when the operation was abruptly stopped for hours due to the unstable subgrade lacking CTB and AB layers above as indicated in the contract drawings. The equipment workability on the compacted subgrade materials was extremely low as they contained an excessive amount of salt, making it difficult to compact to the required density.

If such unfavorable subgrade soils were encountered, the contractor was supposed to excavate another 150 mm of the poor subgrade and replace it with new aggregates. Unfortunately, at the time of the first weekend closure, Caltrans and the contractor could not agree on a contingency procedure for the subgrade remediation due to a discrepancy in each party's unit cost for aggregate base. Because of time constraints and lack of aggregate stockpiles on hand at the first weekend closure, it was decided to place a 50 mm AR-8000 working platform on top of the poor subgrade without replacing it with new aggregates. In the subsequent extended weekend closures, all unstable subgrade was replaced with new aggregates. Consequently, the excavation quantity increased significantly compared to the initial plan and standby equipment was deployed to handle the additional quantity within the limited time slot.

The placement of new AB was concurrently carried out with the subgrade excavation. During the second and seventh closures, the two demolition/excavation crews placed an average of 1,080 m³ of new aggregates in 9.0 h as scheduled by the contractor. On average, 14.7 truckloads of aggregates (recycled

from PCC slabs removed at the previous weekend closure) were placed onto the subgrade soils with an average truck turnaround time of 1 h and 3 min. By performing both operations simultaneously, the contractor managed to incorporate this activity into the 55-h work schedule without making significant changes.

AC Paving Productivities

CSOL AC Overlay

During each weekend closure, the CSOL paving crew placed an average of 6,523 t of HMA in 18.2 h, 12% faster than the planned 20.7 h. Hourly paving rate ranged between 112.9 and 542.0 t/h with the average rate of 358.4 t/h. The windrow paving process allowed continuous paving operation with minimized truck waiting time. On average, 16.0 double-dump semitractor trailers [also known as semibottom dump trucks (SBTs)] arrived at the paving site per hour and discharged HMA windrows at a rate of about 4 min/truck. With the distance to the batch plant being close to 50 km from the project site, the average turnaround time of HMA delivery trucks was 2 h and 13 min.

FDAC AC Paving

The FDAC paving crew, who finished the CSOL AC overlay at first, placed an average of 4,763 t of HMA in 18.3 h during each weekend closure, 20% slower than the planned 15.3 h. The hourly paving rate varied between 33.3 and 472.9 t/h with the average rate of 259.8 t/h. On average, 11.6 truckloads of HMA were placed per hour with about 5 min discharging time per truck. The average turnaround time of the HMA delivery trucks was 2 h and 26 min.

The average hourly paving rate at the FDAC sections was about 28% less than that observed at the CSOL sections. The unstable subgrade condition was one of the main reasons for this sharp decrease in the FDAC paving crew performance. For instance, during the first weekend closure, motor graders had to be used to place the AR-8000 working platform and AR-8000 rich bottom course as the paver got stuck repeatedly in the weak subgrade. During AC compaction, subgrade soils were pumped out at some locations and these soils had to be removed manually, causing further delay in progress. The relatively short length (about 400 m) of the FDAC sections also contributed to the paving slowdown as the frequency of paving stoppage (while bringing the paver back to the original starting point after finishing each pull) increased. The FDAC paving crew also experienced difficulty in accommodating changes in pavement alignment within such a short distance.

Use of double end-dump trucks for the delivery of the AR-8000 working platform and AR-8000 rich bottom lift (during the first and second closures only) also contributed to the loss in the FDAC paving productivity. Compared to the CSOL AC overlay operation (i.e., windrow paving process), where multiple SBTs simultaneously laid down HMA windrows, the paving progress was noticeably slower as each end-dump truck had to individually unload the HMA into the paver's hopper. The double end-dump trucks also required a significant amount of setup time to separately unload the HMA in the truck bed and the attached trailer. Based upon its experiences, the contractor expected that use of nonwindrow paving process (with less productive double end-dump trucks) was more appropriate as the two AC lifts would be placed over loosely bound and uneven surface. Starting from the third weekend closure, all AC lifts including AR-8000 rich bottom were placed using the windrow paving process.

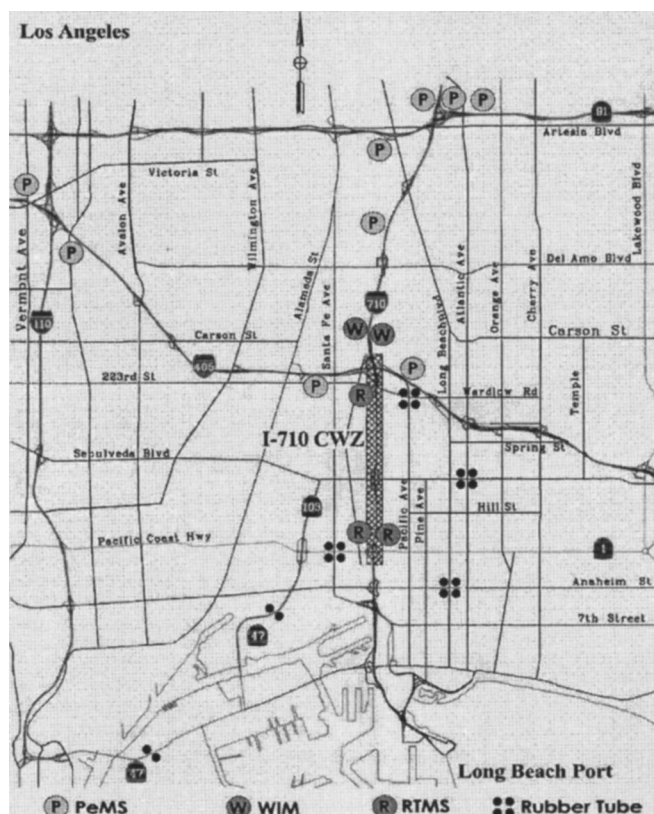


Fig. 4. Traffic study area showing locations of traffic monitoring devices

Traffic Impact Measurement

Monitoring Devices

The traffic impact of 55-h weekend closures was monitored by measuring changes in the traffic network performance (volume, speed, and time) between weekends before and during construction. Traffic measurements were performed throughout all eight weekend closures over the network study area of about 20 km×20 km in size (Fig. 4) to find out any changes in traffic pattern as the weekend closures went on. Traffic surveillance devices utilized included:

1. Loop detectors on the California Freeway Performance Measurement System and weigh-in-motion on the I-710 corridor and neighboring detour freeways;
2. Remote traffic microwave sensors, radar detection devices installed roadside along the CWZ;
3. Rubber tubes to measure a traffic demand change at ramps and intersections on detour arterials; and
4. Tach-run vehicles to measure real-time travel time and speed along the CWZ.

Traffic Study Summary

The results showed a significant reduction in traffic demand (volume) through the CWZ throughout the weekend closures, similar to what was estimated in the TMP. Compared to the historical (before-construction weekends) average rates, 39% decrease in the ADT volume and 37% decrease in the peak hour traffic volume were observed as the freeway users rerouted to local arterials and neighboring freeways (Table 2). During the

Table 2. Comparison of Traffic Flows between Before- and During-Construction Weekends

Period	Traffic measurements	Northbound	Southbound
Weekends before construction	Average daily traffic (vehicles/day)	61,255	61,044
	Peak hour traffic (vehicles/h)	4,299	3,900
Weekends during construction	Average daily traffic (vehicles/day)	38,667	35,544
	Peak hour traffic (vehicles/h)	2,733	3,498
Traffic demand reduction (%)	Average daily traffic	36.9	41.7
	Peak hour traffic	37.2	35.8

weekend closures, the traffic volume on the parallel arterial roads, which were designated as detours in the TMP, increased about 14% on average. However, there was no significant change in traffic volume on the neighboring freeways, except on the parallel Harbor Freeway (Interstate-110) where traffic increased about 7%. Overall, the total traffic demand reduction across the network study area was only about 1%, compared to 5% estimated in the TMP, indicating that the detoured drivers re-entered the freeway via the detour arterial roads around the CWZ.

The results also showed a steady traffic demand increase through the CWZ as the weekend closures were repeated. During the first weekend closure, the peak hour traffic volume was 1,350 vehicles/lane/h. This peak hourly rate gradually increased in the succeeding weekend closures and finally stabilized at around 1,500 vehicles/lane/h, which was believed to be near the maximum traffic capacity under the counterflow configuration with two lanes in each direction. The CWZ traffic increase appeared to reflect the drivers' dynamic response and learning curve as, during the first weekend closure, they observed that delays were not going to be as significant as they had anticipated. Overall, the traffic measurements suggested that the impact of the weekend closures was tolerable as there was no significant congestion and traffic was in free-flow condition throughout the traffic network, including the I-710 corridor, neighboring freeways, and detour arterials.

Lessons Learned and Conclusions

Lessons Learned

Being fast-track construction, the I-710 project emphasized the need for having a comprehensive contingency plan in place against all possible adverse events. The unstable subgrade encountered during the first weekend closure caused a temporary suspension and difficulty in schedule control for the rehabilitation operations at the FDAC section. However, the contractor was able to mitigate some of the geotechnical problems by deploying the backup equipment that was on standby near the site. Prior agreement on the contingency procedures in the event of unstable subgrade could have prevented the loss of productivity at the FDAC sections and helped the contractor to stay on schedule during the first weekend closure.

Use of repeated weekend closures for similar types of rehabilitation operations led to significant improvements in the contractor's production rates (learning-curve effect), especially in the demolition/excavation and paving operations. Between the first and seventh weekend closures, the contractor's demolition/excavation production rate improved about 43%, while the

combined production rate for paving (i.e., average of CSOL and FDAC paving) increased by about 18%.

The notable increase in the demolition/excavation production rate occurred as the contractor made an extra commitment in terms of resources and scheduling after realizing that this operation was the most critical, constraining overall project progress under the unstable subgrade condition. According to the postconstruction interviews with Caltrans construction engineers and the contractor, and comparison with the productivity data collected from the I-10 Pomona and I-15 Devore LLPRS projects, the demolition and paving production rates observed during the seventh weekend closure were believed to be near the maximums possible for fast-track urban freeway rehabilitation in California with the currently available equipment and methods.

The average nighttime paving rate (from 7 p.m. to 7 a.m.) was slightly slower (about 10%) than the average daytime rate at both CSOL and FDAC sections. No noticeable difference in the paving rate was observed between the AR-8000 and PBA-6a asphalt mixes being placed with the windrow paving process. Sometimes, long queues of up to 20 HMA delivery trucks were observed while at other times, the paving crew could not make any progress due to delivery delays. The HMA delivery and paving synchronization problems were mostly caused by lack of coordination between the site and the batch plant rather than traffic congestion on the delivery routes. More efficient coordination between HMA production and paving could have resulted in consistent paving progress and improved the overall paving production rate.

The comprehensive TMP and extensive public awareness campaigns enabled the contractor to have efficient access to the site and minimized the turnaround time of demolition hauling and HMA delivery trucks. The results obtained from implementation of the TMP were considered a complete success as it induced a significant traffic demand reduction through the CWZ, as much as 38% during the weekend peak hours, thus allowing traffic to flow safely without any significant congestion on one side of the freeway while intensive construction progressed on the other side. The project won the 2003 Roadway Workzone Safety Awareness Award in the category of "Innovations in Technology (Methodology—Large Projects)," sponsored by American Road and Builders Association and the National Safety Council. Caltrans utilized the monitored construction and traffic data together with their lessons learned from this I-710 project as a reference in developing construction staging and traffic management plans for the first large-scale LLPRS implementation project on I-15 in Devore (Lee et al. 2005).

The monetary incentives/disincentives proved to be effective in this fast-track rehabilitation project as it inspired creativity and ingenuity on the part of the contractor in reducing the number of

extended weekend closures. The contractor was awarded an incentive amount of \$200,000 for the two weekends early completion and was compensated about \$70,000 extra for exceeding the minimum AC quality control requirements.

Summary and Conclusions

This paper presented the fast-track rehabilitation process and progress that were monitored during the first long-life asphalt concrete pavement rehabilitation project in California. Though there was some schedule delay and cost overrun in the initial preparation phase, the project proved that 55-h weekend closures with counterflow traffic and around-the-clock construction operations is a viable option that can drastically shorten overall construction time and thus lessen traffic inconvenience in urban areas. With completion of the major rehabilitation work two weekends ahead of schedule, it is estimated that millions of dollars were saved in the end from fewer traffic delays and accident exposures for freeway users.

Overall, the productivity monitoring results indicated that the contractor's staging plans for the main rehabilitation work were generally accurate and reliable. Almost all the planned activities were completed during each weekend closure and the freeway was reopened to the public by Monday 5 a.m. after every weekend closure. Use of repeated weekend closures for similar types of rehabilitation operations led to a noticeable improvement in the contractor's production rates in the succeeding weekend closures and enabled the contractor to complete the main rehabilitation work ahead of schedule.

The traffic monitoring results revealed that the comprehensive TMP with proactive public outreach was successful as it induced a significant traffic demand (volume) reduction at the CWZ and the traffic maintained the free flow speed throughout the network study area. The monetary incentive and pay factor proved to be effective as they encouraged the contractor to expedite site operations while ensuring quality workmanship in the accelerated rehabilitation. As fast-track construction, this project emphasized the need for a comprehensive contingency plan in place against all possible adverse events. It is expected that the repeated extended closures with counterflow traffic scheme will be continuously utilized in future long-life urban freeway rehabilitation projects in California.

Acknowledgments

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References

- California Department of Transportation (Caltrans). (1998). *Ten-year state highway system rehabilitation plan 1998-99 through 2007-08*. Maintenance and Transportation Programming, Caltrans, Sacramento, Calif., (<http://www.dot.ca.gov/hq/transprog/reports/tnyrplan.pdf>) (June 10, 2003).
- California Department of Transportation (Caltrans). (2003). *Long Beach Freeway (I-710) pavement rehabilitation, project overview fact sheet*, Caltrans, Sacramento, Calif., (http://cms.longbeach.gov/pw/content/traffic_trans/710projectdescription.htm) (July 28, 2003).
- Deacon, J. A., Harvey, J. T., Guada, I., Popescu, L., and Monismith, C. L. (2002). "Analytically based approach to rutting prediction." *Transportation Research Record 1806*, Transportation Research Board, National Research Council, Washington, D.C., 9–18.
- Lee, E. B., and Ibbs, C. W. (2005). "A computer simulation model: Construction analysis for highway rehabilitation strategies." *J. Constr. Eng. Manage.*, 131(4), 449–458.
- Lee, E. B., Ibbs, C. W., and Thomas, D. (2005). "Minimizing total cost for urban freeway reconstruction with integrated construction/traffic analysis." *J. Infrastruct. Syst.*, 11(4), 250–257.
- Lee, E. B., Mun, J. H., and Harvey, J. T. (2004). "Impact of urban freeway rehabilitation on network traffic: Measurement and simulation study." *Technical Rep. No. TM-UCB-PRC-2004-1*, Pavement Research Center, Univ. of California at Berkeley, Berkeley, Calif. (submitted to the California Department of Transportation).
- Lee, E. B., Roesler, J. R., Harvey, J. T., and Ibbs, C. W. (2002). "Case study of urban concrete pavement rehabilitation on Interstate 10." *J. Constr. Eng. Manage.*, 128(1), 49–56.
- St. Martin, J., Harvey, J. T., Long, F., Lee, E. B., Monismith, C. L., and Herriott, K. (2001). "Long-life rehabilitation design and construction: I-710 Freeway, Long Beach, California." *Transportation Research Circular 503*, Transportation Research Board, National Research Council, Washington, D.C., 50–55.

Integrated Design/Construction/Operations Analysis for Fast-Track Urban Freeway Reconstruction

Eul-Bum Lee¹; John T. Harvey²; and David Thomas³

Abstract: The California Department of Transportation is rehabilitating or reconstructing deteriorated urban freeways using long-life (30+ years) strategies. These pavements were constructed between 1955 and 1970 with design lives of 20 years. This paper summarizes preconstruction analysis of the fast-track pavement reconstruction on Interstate-15 (I-15) at Devore which used two one-roadbed continuous (about 210 h) closures with round-the-clock (24/7) operations. The integrated analysis concluded that the one-roadbed continuous closures are the most economical scenario when compared to traditional nighttime or weekend closures from the perspective of schedule, delay, and costs. The preconstruction was validated with as-built construction and traffic performances monitored during construction. The construction management plan—including contingency, incentives, and critical path method schedule—was developed utilizing the *Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS)* computer model. The results of this planning study are useful for transportation agencies in developing highway rehabilitation strategies that balance the maximization of construction productivity with a minimization of traffic delay.

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CE Database subject headings: Highway construction; Concrete pavements; Fast track construction; Constructability; Reconstruction; Case reports.

Introduction

Pavement Deterioration and Rehabilitation

The 256,000 km of the National Highway System represent 4% of the 6 million km of road in the United States (Bureau of the Census 1994). However this vital infrastructure system carries 75% of all truck traffic and connects 95% of the businesses and 90% of the households in the United States (FHWA 1996). Most of the pavements in this system were originally built between 1950 and 1980 with 20 year design lives, which have now been exceeded. For this reason, the focus of highway construction has shifted from building new transportation facilities to “4-R” projects: restoration, resurfacing, rehabilitation, and reconstruction (Herbsman and Glagola 1998).

When an advanced state of pavement structural damage has been reached, routine maintenance and standard rehabilitation

strategies provide diminishing returns in terms of cost effectiveness for the owner agency, and result in increasing road user costs because of the increasing frequency of lane closures for maintenance and rehabilitation. Thus new strategies must be found to restore long-term functional reliability of the highway pavement. As an additional complication, in 1999–2001 about 30% of the pavements requiring 4-R type construction highway projects were in urban areas, where construction causes serious problems with traffic service for the communities that use the freeways (WisDOT 2002).

A pioneer when it comes to highway construction, the State of California is now faced with widespread deterioration of its highway infrastructure. The California highway system includes over 78,000 lane km, with most built between 1955 and 1975 with the typical 20 year design life. A large number of the pavements in this system have been exposed to heavier traffic volumes and loads than they were originally designed to handle, and are continuing to be made to function 10–30 years after their intended life. Increasing road user costs associated with the aging of the highway network include safety, ride quality, traffic delay, and vehicle operating costs. As traffic volumes continue to soar in California, reconstruction during daytime commute hours becomes ever more unpopular.

In 1998, the California Department of Transportation (Caltrans) launched the Long-Life Pavement Rehabilitation Strategy (LLPRS) program to rebuild approximately 2,800 lane km of badly damaged pavements over 10 years (Caltrans 2003). The criteria for LLPRS candidates were poor structural condition and ride quality and a minimum of 150,000 average daily traffic (ADT) or 15,000 truck ADT. The main goals of the LLPRS program are to provide new pavement with at least 30 years of design life and requiring minimal maintenance. Most of the candi-

¹Research Engineer, Institute of Transportation Studies, Univ. of California at Berkeley, Bldg. 452 (PRC), 1353 S. 46th St., Richmond, CA 94804 (corresponding author). E-mail: eblee@berkeley.edu

²Associate Professor, Dept. of Civil & Environmental Engineering, Univ. of California at Davis, 3139 Engineering III, 1 Shields Ave., Davis, CA 95616. E-mail: jtharvey@ucdavis.edu

³Chief Engineer in Design C, California Department of Transportation (District 8), 464 West 4th St., San Bernardino, CA 92401. E-mail: david_k_thomas@dot.ca.gov

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date projects are interstate freeways in urban corridors in the Los Angeles and San Francisco Bay areas and currently have Portland cement concrete (PCC) pavements.

Innovative Closure Strategies

Traditionally, urban freeway rehabilitation projects in California have used 7 or 10 h nighttime closures because daytime closures cause unacceptable traffic delays during weekday peak travel periods. The disadvantages of nighttime closures include difficulty in controlling construction quality control, which often has detrimental effects on pavement life and surface smoothness, and the severely restricted set of pavement rehabilitation strategies that can be completed and opened to traffic in 7–10 h. These disadvantages make the goal of long-life pavement and minimal maintenance nearly impossible to achieve. Nighttime closures also pose increased safety risks for road users and construction crews. They often result in longer total closure times, higher construction and traffic handling costs, and greater traffic delay to road users (Lee et al. 2000).

In recognition of these problems with nighttime closures, Caltrans has initiated the use on LLPRS projects of innovative pavement rehabilitation strategies (pavement designs and materials) and accelerated construction with 24 h/day operations during multiple 55 h weekends or 72 h weekdays or continuous closures. (In continuous closures, lanes are closed and not reopened until construction is completed.)

The concept of the 55 h extended weekend closure was validated in 2000 on the first concrete LLPRS demonstration project on Interstate 10 in Pomona (Lee et al. 2002), and on the first asphalt LLPRS demonstration project on Interstate 710 in Long Beach, completed in 2003 (Lee et al. 2005b). The time savings of fast-track highway reconstruction with extended longer closures are offset to some degree by the risk of significant traffic disruption if the project's schedule slips. Nevertheless, the study on the I-10 Pomona project showed that construction under the 55 h weekend closure was on average about 40% more productive than traditional nighttime closures.

The Pomona and Long Beach projects formed the baseline for the preconstruction analysis of the reconstruction of Interstate 15 at Devore, the subject of this paper. The Devore project differs from the previous two projects because it employed an integrated and simultaneous consideration of schedule, traffic handling, and cost during development and implementation of the project management plan through the planning, design, and construction phases. Traditional project development and implementation for highway projects typically looks at cost, schedule, and traffic handling sequentially, which often results in decisions being made in each stage that have unintended negative effects on other elements of the project plan.

Integration Approach to Long-Life Pavement Rehabilitation Strategy Projects

Taking more lanes away from traffic facilitates fast construction by providing more space for removal of huge volumes of demolished pavement, delivery of new paving materials, and operation of large numbers of heavy equipment during urban freeway rehabilitation. Traditional design of long-life pavements focuses on thicker layers and high quality materials that often require considerable time to construct. Faster construction requires thinner pavement structures and materials that quickly develop strength to be able to handle construction and road user traffic.

To meet the conflicting design life and constructability goals for LLPRS projects requires innovative pavement designs that provide long life with thinner structural sections, as well as materials that shorten construction and curing time, without sacrificing quality and performance (Roesler et al. 1999). Construction planning must focus on speeding the construction process by incorporating such concepts as contingency management, incentives/disincentives (I/D), and cost (A) plus schedule (B) bidding (Arditi et al. 1997), and by balancing the traffic needs of road users on one side of the lane closure barrier and construction equipment on the other. The integration of pavement design and materials, construction, and traffic analyses provides the basis for an efficient project management plan that minimizes life cycle costs within project constraints.

Research Objectives and Scope

A joint research team from the Univ. of California Pavement Research Center (Berkeley and Davis) conducted integrated analyses of design, construction, and operations in the planning and design stages of the Devore project to help Caltrans refine methods for fast-track pavement reconstruction. The main objective of this preconstruction study was to develop the most efficient construction management plan possible by building on and adding to the practices and lessons learned from the Pomona and Long Beach projects.

In the first step of the analysis, four construction window closure alternatives (i.e., 55 h weekend, 72 h weekday, 10 h nighttime, and one-roadbed continuous closures) were evaluated and compared. The objective was to select the most economical construction closure scenario from the perspective of production schedule, traffic delay (total delay and maximum time spent in a queue), and total costs (the sum of construction and road user costs). Based on the integrated analysis and feedback from public hearings, Caltrans decided to use one-roadbed continuous closures, closing the entire roadbed in one direction of travel and placing traffic traveling in both directions on the other roadbed with a movable barrier separating them. Construction was planned to occur 24 h/day and 7 days/week during each closure.

Then, a more detailed constructability analysis of the selected scenario was performed to refine the construction management plan, especially focusing on the contractor's: (1) logistical resource constraints, (2) incentives/disincentives requirement, and (3) contingency provisions. Results of that analysis were used to develop the project special provisions.

Finally, the preconstruction estimates were compared with the contractor's production performance and traffic delay data collected during monitoring of the reconstruction. A summary of the monitoring data is presented in this paper for comparison with the project plan. Detailed results of construction and traffic monitoring will be presented in another paper as a postconstruction study.

These studies will help Caltrans and other transportation agencies develop better management techniques for fast-track rehabilitation of highways with high traffic volumes.

Construction Analysis for Pavement Rehabilitation Strategies Computer Model

The innovative analysis approach for the Devore project was made possible by the use of a sophisticated production estimation model called Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS). This model was developed by the Univ. of California Pavement Research Center. The software was coded

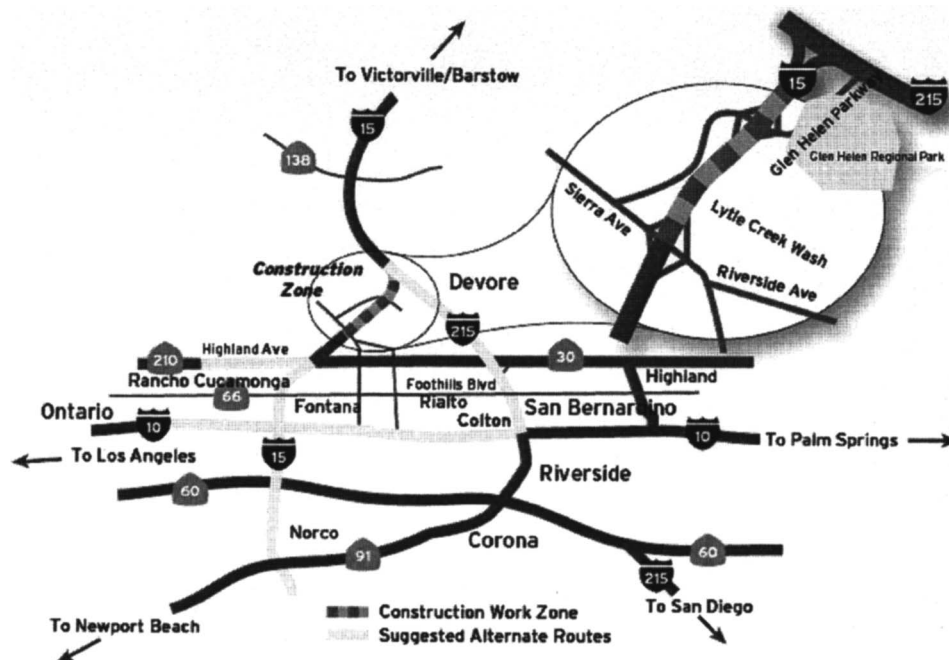


Fig. 1. Site location of I-15 Devore reconstruction project

with support from the State Pavement Technology Consortium (California, Florida, Minnesota, Texas, and Washington), a Federal Highway Administration pooled fund program.

The *CA4PRS* model estimates the maximum amount of highway pavement rehabilitation or reconstruction (lane km and centerline km) that can be completed during various types of closures (Lee and Ibbs 2005) by taking account of project constraints such as scheduling interfaces, pavement materials and design, contractor logistics and resources, and traffic operations. A powerful feature of *CA4PRS* is that it can be integrated with macro- and microscopic traffic simulation models to quantify road user costs during construction. When used with traffic models, the *CA4PRS* software can help determine which pavement structures and rehabilitation strategies maximize on-schedule construction production without creating intolerable traffic delays. This information is vital to balancing the three competing goals of long-life pavement, faster construction, and minimum traffic delay.

The *CA4PRS* model was designed in consultation with the sponsoring state departments of transportation currently engaged in validation and implementation of the software. *CA4PRS* is a planning tool designed to be used during the planning, design, and construction stages. It was validated by the Pomona project, and was used on the Long Beach projects to evaluate construction plans.

I-15 Devore Reconstruction Project

Project Overview

Caltrans District 8 planned to rebuild a 4.5 km section of Interstate 15 (Fig. 1), with construction to be completed in October 2004. Caltrans split the project into two segments for construction staging to facilitate traffic detours using median crossovers. Segment 1, built in 1975, is 2 km long with four lanes in each direction. Segment 2, built in 1969, is 2.5 km long with three lanes in each direction.

The passenger car lanes (inner one or two lanes) in each direction were still in good condition in both segments. The two truck lanes were to be rebuilt or repaired to correct extensive cracking, rough ride, and patches. In the inner truck lane approximately 15% of the total linear length was selected to receive individual slab replacements for the badly cracked slabs. The entire outer truck lanes in each direction were planned to have removal of the lane and reconstruction with new pavement (see Fig. 2).

The Devore corridor carries approximately 110,000 ADT, with about 10% heavy trucks. In contrast to typical urban freeways in California, which typically have low traffic on weekends and high traffic during rush-hour weekday peak periods, the Devore corridor has both very high weekday commuter peaks and high leisure traffic volume on weekends. The two highest peak traffic volumes are northbound on Friday afternoon and southbound on Sunday afternoon, when leisure travelers in the Los Angeles, Calif. area are going to and from Las Vegas, Nev.

Construction Work-Zone Closure

The existing and replacement structures for the outer truck lanes are shown in Fig. 3. The Old Section is a typical 1970s Caltrans design, using undowelled plain jointed concrete slabs. The New

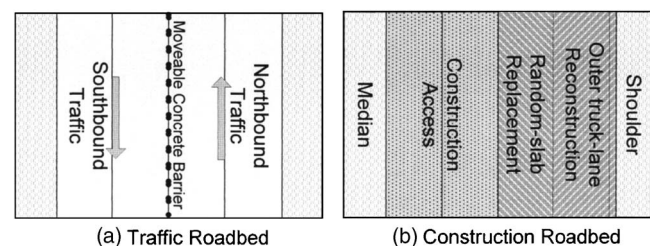


Fig. 2. Plan view of construction and traffic roadbeds in segment 1

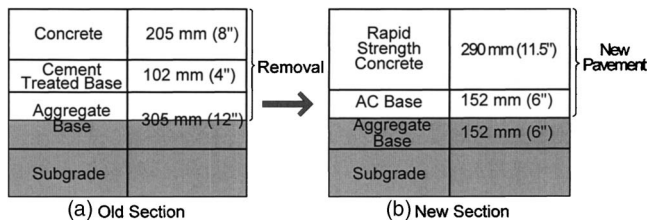


Fig. 3. Change of concrete pavement cross section

Section uses concrete mixes with high early strengths, and includes placement of asphalt concrete (AC) base between the slabs and remaining old aggregate base.

The construction staging required the northbound freeway to be closed for reconstruction first, switching traffic to the other side (southbound) through the median crossovers at the ends of Segments 1 and 2. As illustrated on Fig. 2, construction occurred on the two truck lanes while the two inside lanes were used for access by construction trucks and other equipment.

The two directions of traffic shared the southbound lanes, separated by a moveable concrete barrier (MCB), a system referred to as “counterflow traffic.” Ramps in the work zone were closed to traffic other than construction equipment.

The outside shoulder was used as a traffic lane in Segment 2 to get two lanes for each direction of traffic. The same process was repeated for the reconstruction of the other direction (southbound).

Most Economical Closure Scenario

The benefits to traffic of using 55 h weekend closures instead of weekday nighttime closures, which are obvious for most Southern California freeways, were not as clear for the Devore project because of its unique traffic patterns. Four construction closure scenarios were compared from the perspective of construction schedule, traffic inconvenience, and agency costs:

- 72 h weekday (Tuesday–Thursday);
- 55 h weekend (Friday–Sunday);
- one-roadbed continuous (about 9 days); and
- 10 h nighttime closures.

The *CA4PRS* model was used to estimate the total number and duration of closures for each closure scenario. Traffic analysis was then performed for each closure scenario to calculate total traffic delay and maximum delay (queue length) per closure, using a demand-capacity spreadsheet model based on the *Highway capacity manual* (Transportation Research Board 2000) with the hourly distributions of freeway traffic data particular to each closure.

Cost projections in most states and on many projects in California typically include only agency costs (construction and traffic handling). Caltrans recognized that, at least for LLPRS projects, the cost of additional traffic delay caused by highway construction to road users is as important as agency cost. There are other road user costs (RUCs) associated with highway construction projects, however, only construction related traffic delay costs were considered because of the difficulties of calculating other costs, and traffic delay costs are generally the largest.

The total cost, calculated as the sum of the agency cost and RUC, was used to select the most economical closure scenario. Using a combined total cost for selection and giving agency and road user costs equal weighting is unusual in selecting highway construction alternatives. The road user cost was calculated using typical values used in Caltrans studies for commercial (\$24/h) and private (\$9/h) vehicles. Table 1 shows the result of the comprehensive comparison from the perspectives of schedule, traffic delay, and total cost used to select the most economical closure scenario (Lee et al. 2005a).

The one-roadbed continuous closure scenario was selected as the best candidate strategy in terms of agency, road user, and total costs. The analysis shows that the one-roadbed continuous closure scenario is about 26% more economical from the total cost (\$20 million versus \$27 million) perspective when compared with the 55 h weekend closures. The one-roadbed continuous closure scenario requires 81% less total closure time, 29% less road user cost due to traffic delay, and 28% less agency cost for construction and traffic control compared to traditional 10 h nighttime closures.

Constructability Comparison

More detailed constructability and productivity analyses were performed using the *CA4PRS* model after selection of the most economical reconstruction closure scenario. The constructability analysis compared the following alternatives for the new pavement from the production and scheduling point of view:

- concrete mix design (cement strength gain time);
- pavement base type (asphalt concrete base versus lean concrete base); and
- outer truck lane width (widened truck lane versus tied concrete shoulder)

The underlying assumption in the constructability analysis, based on earlier studies and laboratory and field tests for LLPRS projects, was that using these three comparison criteria in all alternatives would provide similar pavement performance and life expectancy (Roesler et al. 1999). The scheduling analysis with *CA4PRS* answered the question of how quickly the whole project

Table 1. Schedule, Delay, and Cost Comparison for Closure Scenarios

Closure scenario	Schedule comparison		Traffic comparison ^a		Cost comparison	
	Closure number	Closure hours	Road user cost (\$million)	Peak delay (min)	Agency cost ^b (\$million)	Total cost ^c (\$million)
One roadbed continuous	2	400	5	80	15	20
72 h weekday	8	512	5	50	16	21
55 h weekend	10	550	10	80	17	27
10 h nighttime	220	2,200	7	30	21	28

^aWith assumption of 20% traffic demand reduction.

^bEngineer's reestimate based on the unsuccessful first round of bid.

^cTotal cost=road user cost+agency cost (per row).

could be completed for each permutation of the three variables by estimating the maximum production (distance) per closure and the total number of closures to complete the entire project.

Based on the constructability analysis results, Caltrans decided to use (1) Type III concrete mixes, (2) asphalt concrete base, and (3) a widened truck lane. Details of the constructability analysis are summarized in the following section.

Concrete Mix Design

Two concrete mix designs were compared for the slabs: rapid strength concrete (Type III PCC) which allows opening to traffic within 12 h of placement and fast-setting hydraulic cement concrete (FSHCC) which allows traffic opening within 4 h. The 8 h time advantage of FSHCC is offset by higher concrete slump and material stickiness, the need for more delivery trucks and a smaller paving machine, the restriction to single-lane paving at one time, and the typically rougher finished surface which frequently requires diamond grinding after curing. In addition, FSHCC is about twice as expensive as Type III PCC in California. The *CA4PRS* model indicated that the two materials result in approximately the same overall project completion time.

Pavement Base Type

Two types of base material were considered for the project: asphalt concrete base (ACB) and lean concrete base (LCB). The *CA4PRS* model estimated that significantly more time would be needed if LCB was used instead of ACB because the LCB requires a 12 h curing time before PCC slab paving. The LCB also requires placement of a bond breaker to minimize friction between the base and slab that increases the risk of early-age cracking, which would slow production. The ACB scenario also permits parallel production of the base and slabs, with each operation utilizing its own resources, while the LCB needs to use the PCC plant and paver.

Pavement Structure Design

Two options were considered for the width of the outside truck lane: normal width 3.7 m slabs tied to new concrete shoulder; or a widened truck lane (4.3 m). The schedule analysis showed that the tied concrete shoulder option would slow construction, and require additional closures.

Slab Demolition Methods

Two types of demolition methods for old PCC pavement are commonly used in California: “nonimpact demolition,” in which each slab is cut into three or four large pieces which are lifted out by an excavator; and “impact demolition,” in which the slabs are broken into small pieces by a breaker (rubblizer or stomper) and scooped out by the excavator. Nonimpact demolition used on the Pomona project (Lee et al. 2002) was 58% slower than impact demolition on the Long Beach project (Lee et al. 2005b). However, the non-impact demolition method was selected for the Devore project because it was determined that the noise made by the slab rubblizer during the night could disturb residents and wildlife habitat in environmentally sensitive areas near the site.

Reconstruction Process and Productivity

The expected reconstruction process and construction staging plan for the Devore project, based on the previous LLPRS projects, was outlined and distributed to the contractors in the prebid meeting as a guideline and reference.

Reconstruction Process

The Devore reconstruction project involved three main operations: closure mobilization, pavement reconstruction during main closure, and closure demobilization. The expected detailed activities are as follows:

1. Closure mobilization operation:
 - (1) set up construction work zone signs,
 - (2) set up MCB on the traffic roadbed,
 - (3) remove lane marking and temporary restriping of the traffic road bed; and
 - (4) partial closure of the traffic roadbed.
2. Main reconstruction operation:
 - (5) full closure of construction roadbed and switching of traffic to the traffic roadbed;
 - (6) saw-cut old PCC slabs;
 - (7) cold plane (milling) old outside AC shoulder;
 - (8) demolition of old PCC slabs and excavation of CTB and part of aggregate base (AB);
 - (9) grade and compact AB;
 - (10) production and delivery of hot mix asphalt;
 - (11) pave new AC base (76 mm thick \times 2 lifts);
 - (12) compaction and cooling of AC base;
 - (13) production and delivery of concrete;
 - (14) new PCC slab paving;
 - (15) finishing and spreading the curing compound;
 - (16) PCC slab curing;
 - (17) saw cut new PCC slab joints;
 - (18) AC overlay of outside shoulder; and
 - (19) clean up of the newly constructed pavement.
3. Closure demobilization operation:
 - (20) mark lanes (striping) on the new pavement;
 - (21) open the construction roadbed to traffic;
 - (22) partial closure of the traffic roadbed;
 - (23) remove MCB on the traffic road bed;
 - (24) remove temporary lane marking and restriping on traffic roadbed; and
 - (25) open both directions of the freeway.

Construction Staging Plan

Primary pavement reconstruction activities during the one-roadbed continuous closure included the following:

- Demolition of the existing old pavement structure;
- Paving AC base;
- Paving PCC slab; and
- Cold plane and AC overlay of the outside shoulder.

These four activities were expected to progress concurrently, although equipment could not work at the same location. Based on the linear scheduling technique, one activity followed the other while maintaining a distance and time buffer to avoid interference between the activities. A rehabilitation technique known as the “concurrent double-lane paving method” with a slip form paver was used for this project since two passenger lanes are available for construction access to rebuild two truck lanes at once (Lee and Ibbs 2005). This allows demolition, ACB paving, and PCC paving to proceed simultaneously.

As the *CA4PRS* production analysis estimated, each segment during the one-roadbed closure was subdivided into equal sections approximately 500 m long for construction convenience. The ACB paving was to begin following demolition once the demolition operation progressed far enough (about 500 m) that equipment interferences are minimized and ACB operations

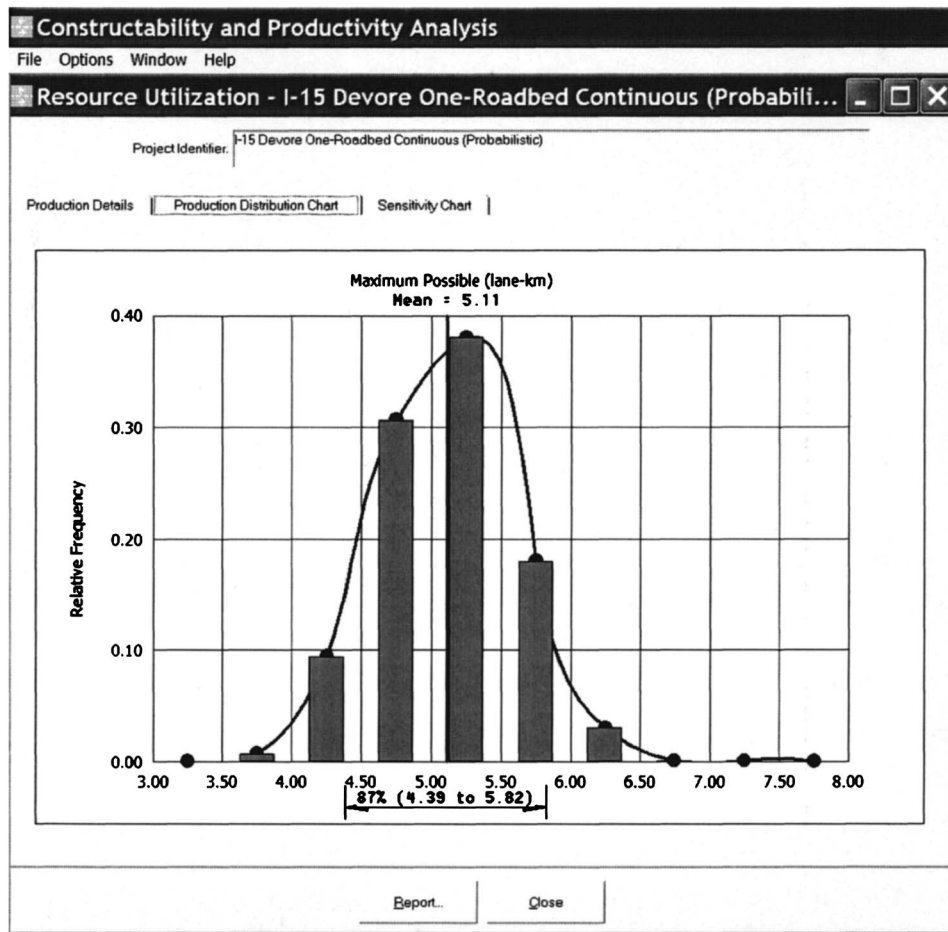


Fig. 4. Output screen of CA4PRS production analysis

would not catch up with the demolition activities. Similarly, PCC paving began and followed ACB paving once ACB paving progressed sufficiently.

Productivity Estimate with CA4PRS

The CA4PRS software was used for the preconstruction productivity analysis. The hourly production rate and resource constraints used in the CA4PRS analysis were confirmed by Caltrans construction engineers and paving contractors (Western States Chapter of the American Concrete Pavement Association) through a series of constructability meetings prior to construction.

Fig. 4 shows an example output screen from the stochastic CA4PRS analysis, which calculates the likelihood of maximum production capability per one-roadbed continuous closure. The CA4PRS model estimated that about 200 h of operations with lead-lag time relationship between main activities were needed to finish 5.1 lane km (including the random slab replacement) of each roadbed closure (one complete direction finished in each closure), with a total closure time of 210 h when mobilization and demobilization were included. A baseline critical path method schedule was developed using the CA4PRS production analysis.

The following sections summarize the CA4PRS productivity analysis.

Portland Cement Concrete Demolition Productivity

Two demolition teams were assumed in the CA4PRS analysis based on the previous LLPRS projects. Each demolition team was

assumed to use an excavator (backhoe) for loading and ten 22 t capacity end dump trucks for hauling operations. Previous case studies showed that ten end dump trucks per hour per team is generally the maximum possible productivity for nonimpact demolition because at least 5 min of cycle time was required to load each haul truck (Lee et al. 2002).

The CA4PRS analysis model utilizing the linear scheduling technique identified balancing resource requirements for the other two major operations (demolition and PCC paving) based on number of haul trucks as the critical resource constraint. The balanced productivity, i.e., hourly progress of the demolition calculated from the analysis with the given hauling volumes, scheduling, and resource constraints, is 100 m/h on average.

Asphalt-Concrete Base Paving Productivity

The CA4PRS analysis indicated that the resources needed for the ACB paving and paving of new AC shoulders to balance with the demolition and paving operation are six 24 t bottom dump semi tractor trailers per hour on average. The AC batch plant needs to produce 150 t/h to keep up with paving operations. The AC cooling time was calculated to check any time delays in starting PCC slab paving using the "MultiCool" cooling analysis program integrated into CA4PRS (Timm et al. 2001). The productivity analysis indicated that each 500 m section of ACB can be paved in approximately 5 h, which itself is not expected to be a production constraint.

Portland Cement Concrete Paving Productivity

The *CA4PRS* analysis estimated that 20 6.5 m³(15 t) dump trucks are needed each hour on average for concrete delivery to achieve the overall maximum production for the PCC slab paving operation. This means each delivery truck has about a 3 min cycle time for concrete charging in the batch plant and also for discharging time on site. This cycle time was validated in the previous case studies and confirmed by the industry group in the constructability meetings as the minimum practically achievable, using a batch plant producing at least 120 m³/h per hour.

The slip form paver must pave at least 1.7 m/min to match production. The paver speed was confirmed to not be a constraint, even with the two-lane concurrent paving, which is typical of projects evaluated to date.

In summary, the balanced progress of the PCC slab paving operation with given resource constraints was estimated to be 100 m/h on average by the *CA4PRS* analysis.

Contingency Plan

The criticality of achieving accelerated construction on the Devore project required specific contingency strategies to minimize the number and magnitude of unforeseen problems and hidden risks. Critical items for this contingency plan were determined based on the previous LLPRS case studies. Some key requirements contractually imposed on the contractor in the project special provisions are summarized below.

Poor Subgrade Replacement

As-built plans for the existing pavement structure on the construction corridor show 200 mm PCC over 100 mm CTB over AB. However, this pavement was constructed in the 1960s and 1970s, and accurate as-built construction records were not available. At some locations poor subgrade might be encountered during demolition and excavation as was observed on the Long Beach project (Lee et al. 2005b). Therefore, contingency planning required pre-planned solutions to potential problems identified during the contingency planning. Additional geotechnical site investigations were performed prior to construction, including coring in the mainline and shoulder and trench investigation in the shoulder to evaluate site conditions.

These activities might delay the schedule and add to the cost. To compensate for any delay, the contractor was allowed to use FSHCC for some sections.

Appropriate Gap between Operations

To minimize equipment interruptions, a minimum gap was required between the locations where major reconstruction operation activities (demolition, AC base paving, and PCC paving) are proceeding concurrently. As noted previously, it was recommended that each segment be divided into four equal sections (about 500 m) and that these activities occur in different sections concurrently. At the same time, the gap between demolition and AC base paving or PCC slab paving also was limited to a certain distance that in the event of an unforeseeable breakdown of a paving operation the demolished pavement could be repaved before the end of the closure. The contingency plan included the use of temporary paving material for that section.

Use of Two Concrete Mixes

The use of FSHCC mix on the final slabs of each closure within 12 h of traffic opening is referred to as the “stitch,” which can save paving hours. The project special provisions allowed the contractor to use different types of cement concrete materials. The FSHCC was allowed on the stitch, either to achieve more production at the end of the closure, to make up for any unforeseen delay, or as a temporary paving material in case of an emergency. The contractor was required to arrange an appropriate set of resources, such as delivery trucks and paving machines to handle these two different mix designs.

Standby Paving Materials for Emergencies

Caltrans decided to retain the contractual authority to open the freeway prior to the end of closure due to emergencies, for example due to severe weather, fires, vehicle accidents, or construction-related problems that would compromise the quality of the finished product. Under such circumstances, the contractor was required to use FSHCC, hot mix asphalt, or cold mix AC as temporary paving materials to be eventually replaced with specified materials.

Incentives/Disincentives Contract

Traditional Caltrans practice for rapid highway rehabilitation projects has been to rely on ad hoc estimates in developing incentives/disincentives to promote the production objective, often without quantitative calculations. The Devore project incorporated the unique approach of using the additional cost associated with road user traffic delay to develop the incentives/disincentives requirement. The assessment of incentives/disincentives was based on the *CA4PRS* production schedule and traffic simulation analyses (Lee et al. 2005a).

Due to a high demand of traffic volume during closures and the public desire for early completion of the reconstruction, Caltrans decided to apply two types of incentives/disincentives provisions to encourage the contractor to complete the closure earlier or on time. The primary provision paid incentives to minimize the duration of each roadbed closure. The secondary provision paid incentives to minimize the total closure days of the entire main reconstruction.

The projected road user cost using the demand-capacity spreadsheet based on the *HCM* model was used as the baseline of the incentives/disincentives calculation for the one-roadbed closures. However, only one third of the road user cost was factored into the incentives/disincentives calculation, a commonly used practice in other states. The incentives were limited by the realities of the budget limitations of the State, and a value of \$600,000 was used for the incentive cap.

The contractor would be eligible for a closure incentive bonus of \$300,000 if one-roadbed continuous closure is completed in equal or less than two units of time segment (111 h/unit), or be subject to a closure disincentive penalty without a limit if the closure takes longer than three units of time segment (one extra was given for realistic flexibility). In addition to this closure incentives requirement, the contractor would be eligible to receive a daily incentive bonus of \$75,000 if the entire major reconstruction was completed in fewer than 19 days (total 456 h), or be subject to a daily disincentive penalty (without a limit) if the reconstruction took longer.



Fig. 5. Construction and traffic operations during I-15 Devore reconstruction

Validation of Preconstruction Analysis

Successful Project Completion

Initially, Caltrans moved ahead assuming the use of 72 h weekday closures due to major concern about traffic delay on weekends for Las Vegas, Nev. bound leisure traffic. However, Caltrans met with strong opposition to the 72 h weekday closures from weekday commuters, which surfaced at public hearings. Weekday commuters felt that their time delay was of greater value than that of leisure traffic. Although the contract was awarded based on the 72 h weekday closures, Caltrans adjusted the reconstruction plan to one-roadbed continuous closures just 1 month before the first extended closure was set to begin. The one-roadbed continuous closure was expected to result in longer queues, but balanced traffic delay to both weekday commuters and weekend leisure traffic, and shortened the total project duration.

Eventually, the reconstruction project was successfully completed with two one-roadbed continuous closures with round-the-clock-operation in October 2004 (Fig. 5). The northbound reconstruction was completed in 216 h. The southbound reconstruction was finished in 210 h several weeks later.

Validation of Preconstruction Analysis

Construction and traffic monitoring studies by the research team during reconstruction confirmed that the overall performance of the reconstruction was consistent with the outlined schemes in this preconstruction analysis with respect to construction process and progress. The *CA4PRS* model underestimated production by about 5%, which is reasonable for a planning tool. The number of hauling and delivery trucks per hour turned around for the major reconstruction operations were similar to the assumed resource inputs in the *CA4PRS* model.

The overall impact of reconstruction closures on traffic was “acceptable” according to a traffic measurement study and web surveys during and after the construction. In fact, the maximum peak hour delay (although very infrequent) was measured at about 75 min on weekends (northbound) and about 45 min on weekdays (southbound). It turned out that about 20% reduction in actual traffic demand during the one-roadbed continuous closures (10% greater than the reduction initially expected) resulted in less in-

convenience to motorists than had been anticipated. The reduction was attributed to Caltrans’ proactive public outreach and traffic control efforts. What could have been potentially grievous public relations resulted in mostly complimentary feedback for Caltrans for keeping traffic moving during the closures.

Technical reports are currently being prepared to summarize state-of-the-practice technology and innovation applied in this fast-track highway reconstruction project. Some examples of the state of the practice products implemented on this project included:

1. Automated work zone information systems that provided travelers through the construction work zone with near real-time travel time and detour routes information displayed on the permanent and changeable message signs, and
2. Extensive public outreach efforts including a project website (with about 100,000 visits in October) on the Internet that featured a live traffic roadmap [displayed with closed circuit television (CCTV)] and construction sequences and public updates (Caltrans 2004).

Conclusions

The conclusions of the preconstruction analysis for the Devore project, since validated by the actual construction, are summarized as follows:

1. The integrated analysis concluded that the one-roadbed continuous closure scenario is the best candidate strategy in terms of agency, road user, and total costs. For example compared to traditional 10 h nighttime closures, the one-roadbed continuous closure scenario requires 81% less total closure time, 29% less road user cost due to traffic delay, and 28% less agency costs for construction and traffic control.
2. A detailed constructability and productivity analysis was implemented using the *CA4PRS* model to develop a construction management plan for the project. Furthermore, a typical reconstruction process was defined, the CPM schedule was developed, and major input resource requirements were outlined.
3. A contingency plan, which was necessary due to the project’s tight schedule and production goals, was developed to minimize the impact of unforeseen problems. A baseline for the incentives/disincentives was developed with an innovative approach based on *CA4PRS* analysis of expected construction duration, and traffic delay analysis and traffic delay cost estimation.
4. The *CA4PRS* model has been shown to be an invaluable schedule analysis tool and is recommended for use on future high-volume urban freeway reconstruction projects. The production estimation with *CA4PRS* was accurate enough (production was about 5% underestimated) as a planning tool, compared with the contractor’s as-built production performance of the one-roadbed continuous closures.
5. Constructability technical experts have been involved from the initial planning stage to identify project constraints and to mitigate obstacles for this rapid reconstruction. The agency has continued the partnership and communication with the paving industry to maximize constructability benefits.
6. The advantages of using this method of accelerated construction were: shortest period of disruption for the traveling public; greater life expectancy for the new pavement than could have been obtained using nighttime closures; improved

safety for motorist and workers; and significantly reduced construction costs (about \$6 million).

7. California now has a unique opportunity to validate and further calibrate the processes, tools, and expertise used in this integrated preconstruction analysis. Thus, postconstruction reports are being prepared to gather "lessons learned" based on the construction/traffic monitoring study from this project for future LLPRS projects.

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References

- Arditi, D., Khisty, J., and Yasamis, F. (1997). "Incentive/disincentive provisions in highway contracts." *J. Constr. Eng. Manage.*, 123(3), 302–307.
- Bureau of the Census. (1994). *Statistical abstracts of the United States 1994: The national data book*, U.S. Department of Commerce, Washington, D.C.
- California Department of Transportation (Caltrans). (2003). "Long-life pavement rehabilitation strategies." Sacramento, Calif. <http://www.dot.ca.gov/research/roadway/llprs/llprs.htm> (October 1).
- California Department of Transportation (Caltrans). (2004). "I-15 Devore Rapid Rehab Project." Sacramento, Calif. <http://www.dot.ca.gov/dist8/i15devore/> (October 3).
- Federal Highway Administration (FHWA). (1996). "Public roads." *J. Highway Research Development*, 59(3), winter.
- Herbsman, Z. J., and Glagola, C. R. (1998). "Lane rental—Innovative way to reduce road construction time." *J. Constr. Eng. Manage.*, 124(5), 411–417.
- Lee, E. B., and Ibbs, C. W. (2005). "A computer simulation model: Construction analysis for highway rehabilitation strategies (CA4PRS)." *J. Constr. Eng. Manage.*, 131(4), 449–458.
- Lee, E. B., Ibbs, W., Roesler, J., and Harvey, J. (2000). "Construction productivity and constraints for concrete pavement rehabilitation in urban corridors." *Transportation Research Record*, 1712, Transportation Research Board, Washington, D.C., 13–22.
- Lee, E. B., Ibbs, C. W., and Thomas, D. (2005a). "Minimizing total cost for urban freeway reconstruction with integrated construction/traffic analysis." *J. Infrastruct. Syst.*, in press.
- Lee, E. B., Lee, H. J., and Akbarian, M. (2005b). "Accelerated pavement rehabilitation and reconstruction with long-life asphalt concrete on high-trafficked urban highway." *J. Transportation Research Board*, in press.
- Lee, E. B., Roesler, J. R., Harvey, J. T., and Ibbs, C. W. (2002). "Case study of urban concrete pavement reconstruction on Interstate 10." *J. Constr. Eng. Manage.*, 128(1), 49–56.
- Roesler, J. R., Harvey, J., Hung, D., du Plessis, L., and Bush, D. (1999). "Evaluation of longer-life concrete pavements for California using accelerated pavement testing." *Proc., Accelerated Pavement Testing International Conf.*, Reno, Nev.
- Timm, D., Voller, V., Lee, E. B., and Harvey, J. (2001). "MultiCool: A numerical solution program for multi-layer cooling time of asphalt concrete pavement." *Int. J. Pavement Eng.*, 2(3), 169–185.
- Transportation Research Board. (2000). *Highway capacity manual (HCM)*, National Research Council, Washington, D.C.
- Wisconsin Department of Transportation (WisDOT). (2002). "Plans & projects: Existing highways." Madison, Wis. <http://www.dot.wisconsin.gov/projects/state/sixyear/hwys.htm> (June 12).